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ROYAL AERONAUTICAL SOCIETY 1866

Journal

of

THE ROYAL AERONAUTICAL SOCIETY

MAY 1956

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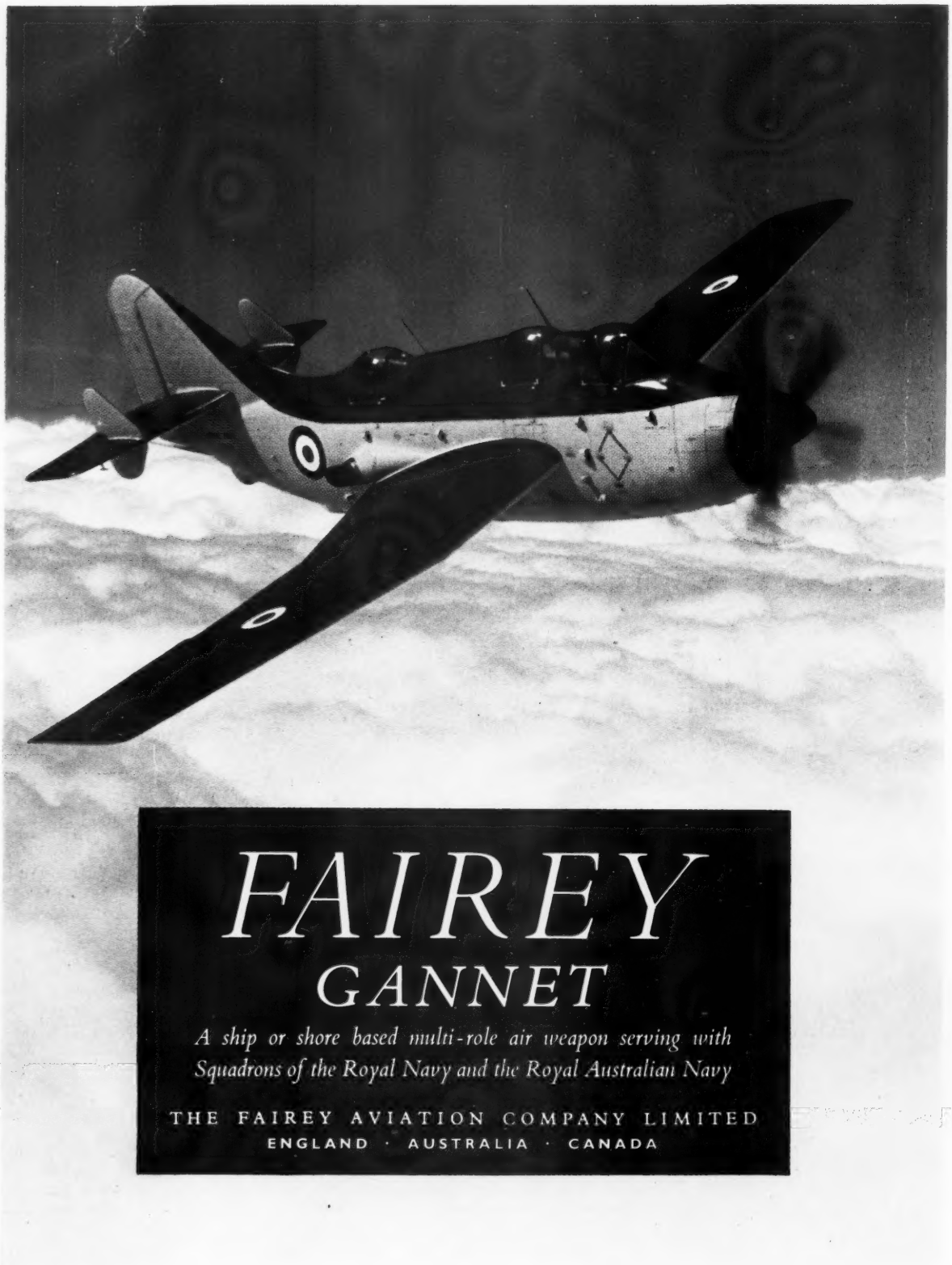
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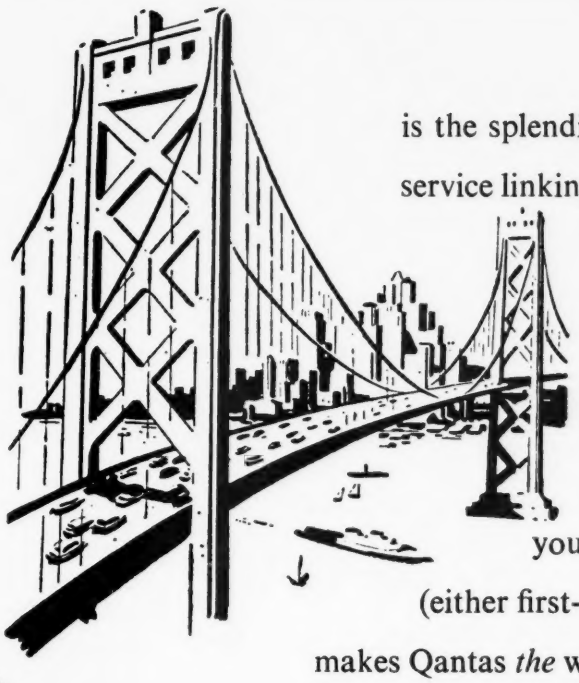

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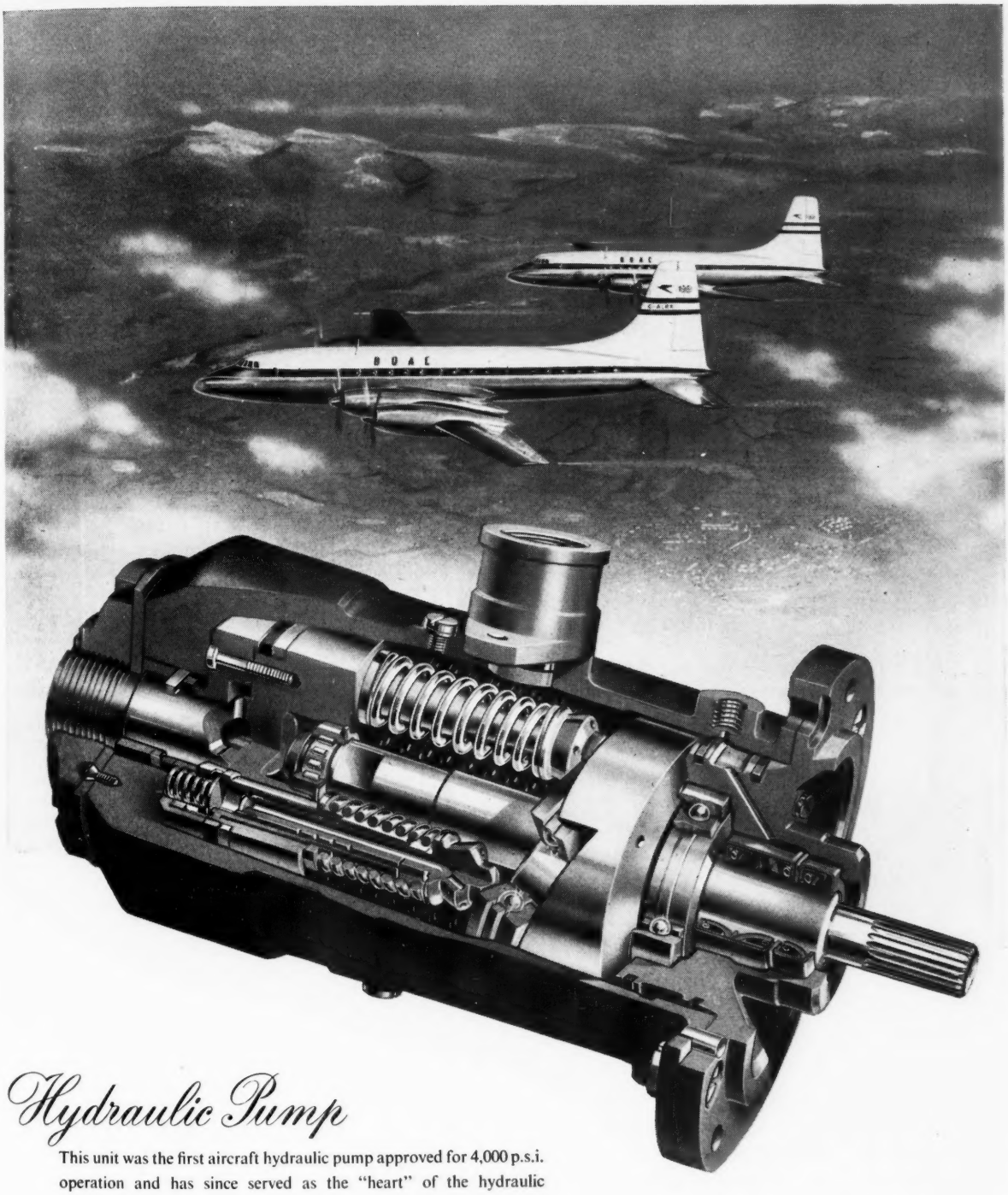

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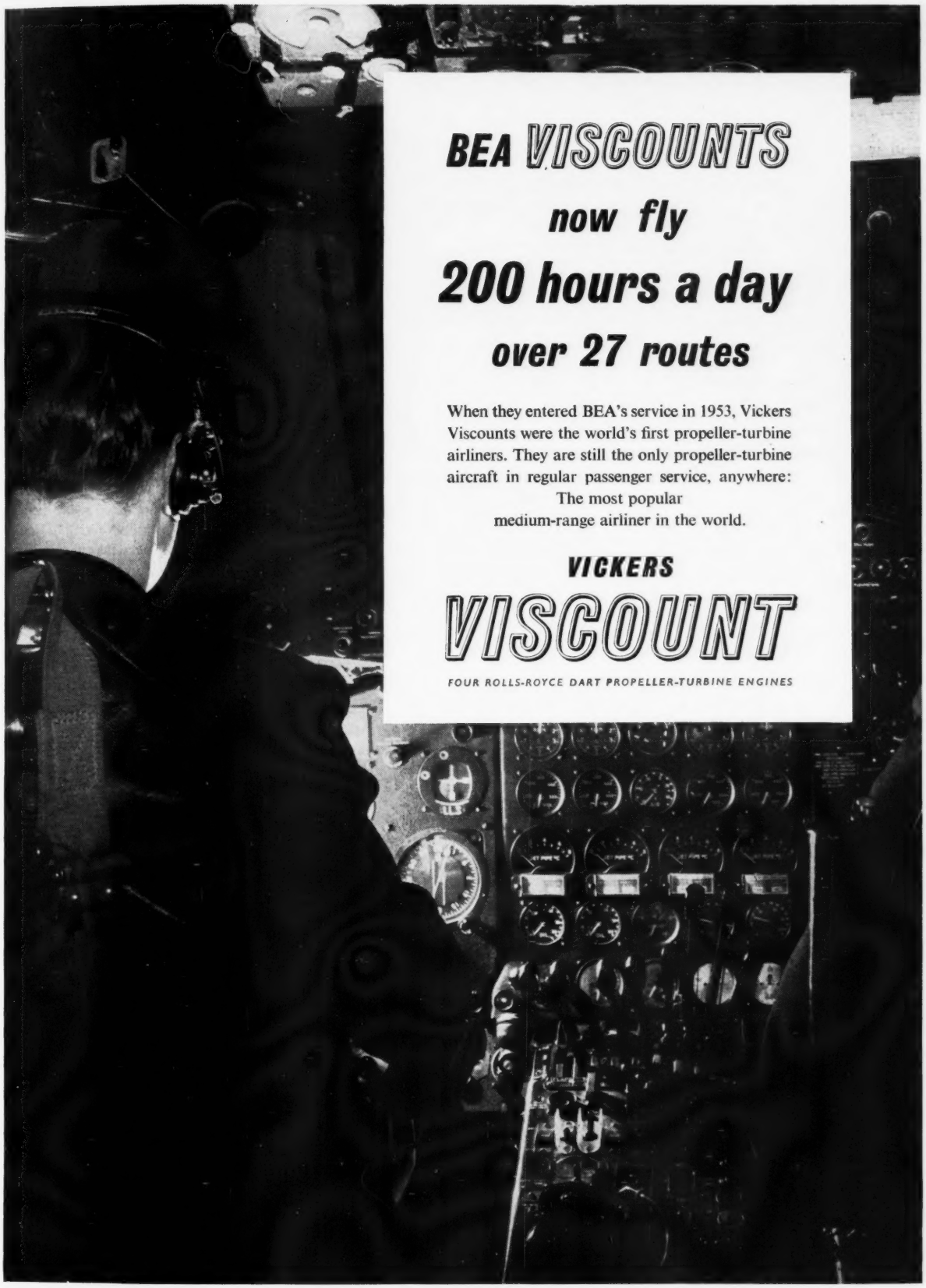
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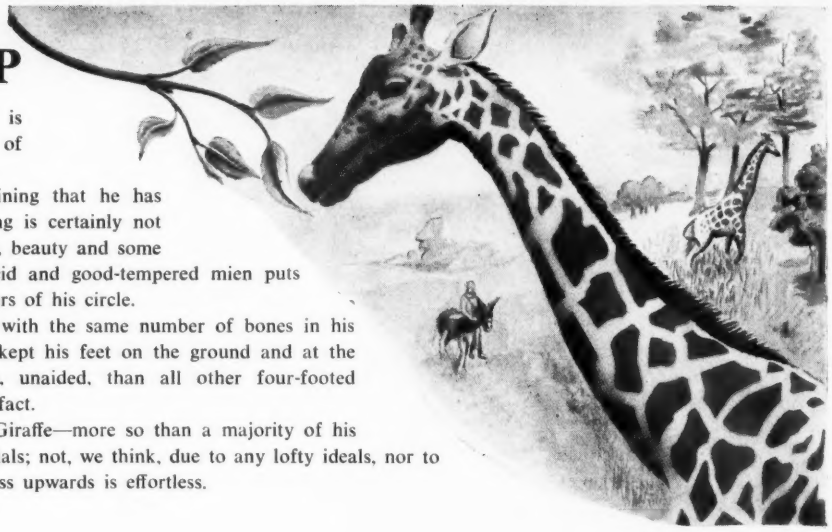

Born of high parentage, the Giraffe is able to hold up his head in the face of all criticism.

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Bearing in mind that he is equipped with the same number of bones in his neck as ourselves (i.e. seven) he has kept his feet on the ground and at the same time reached further upwards, unaided, than all other four-footed animals—eighteen to nineteen feet in fact.

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(*i*) The rolling derivatives of swept and tapered wings

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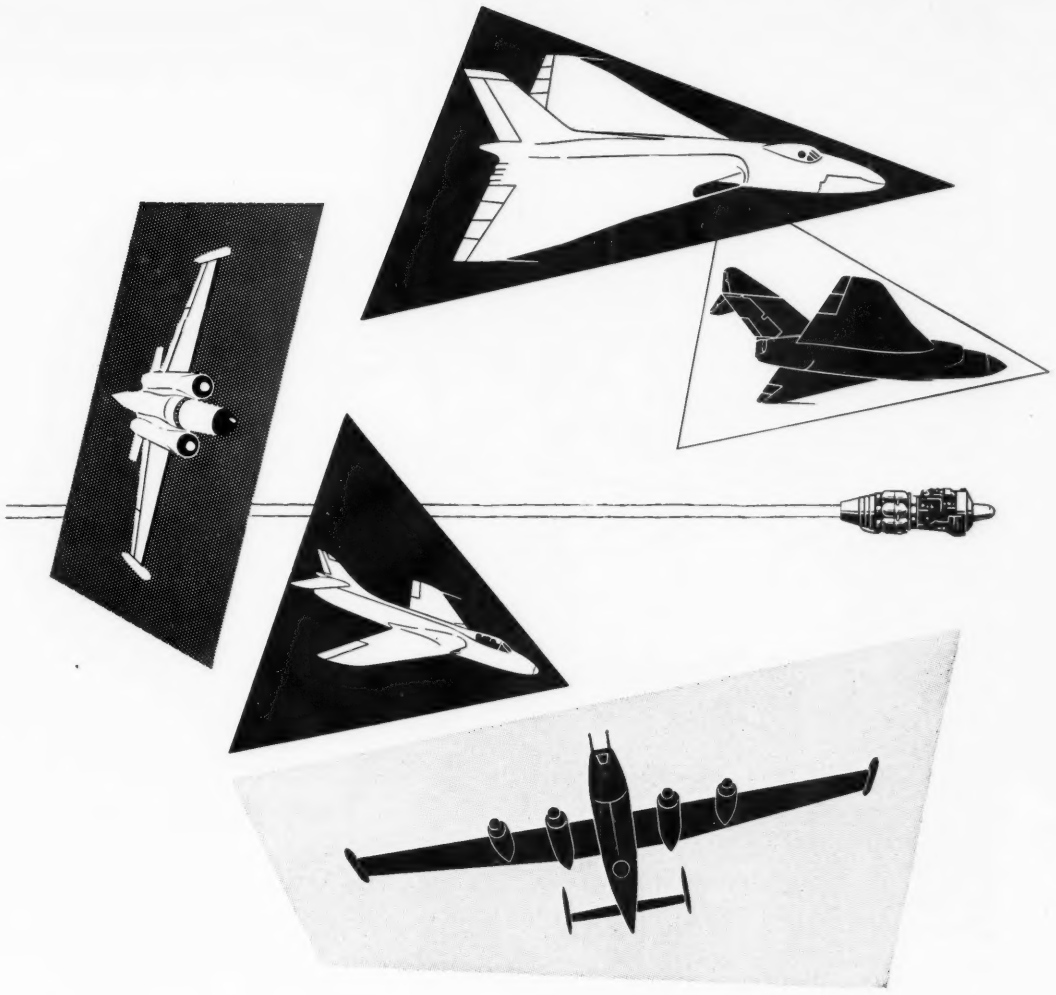

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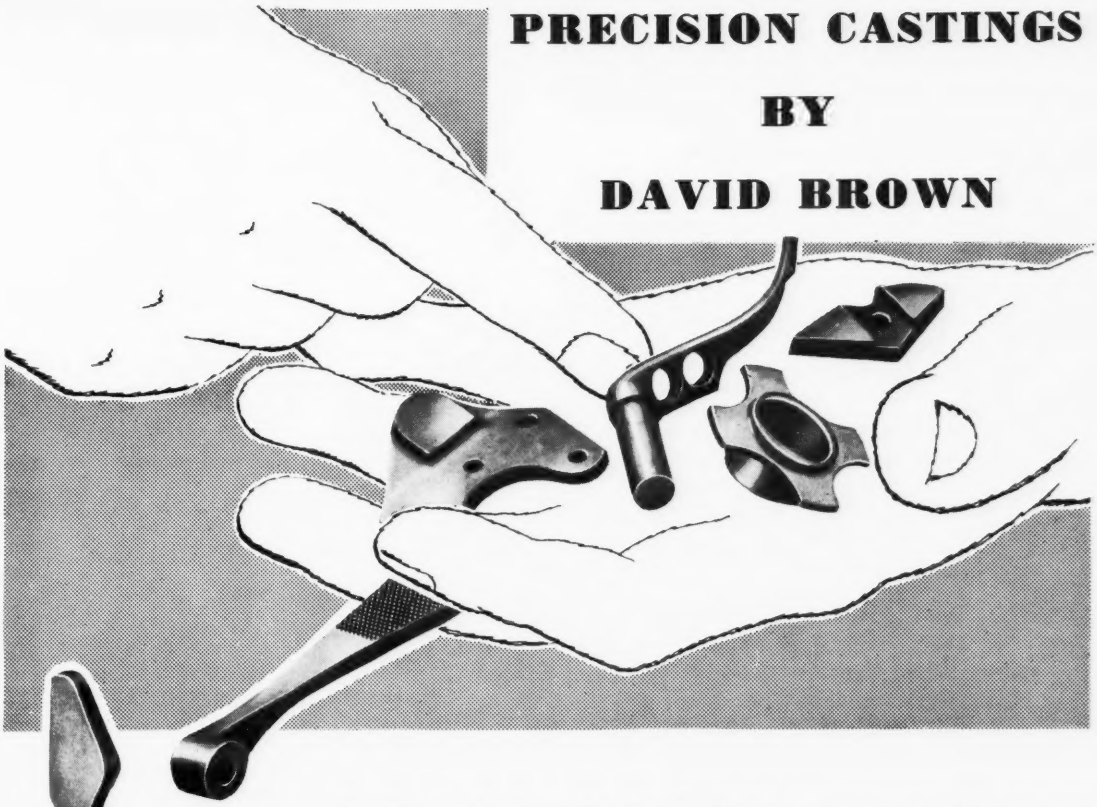

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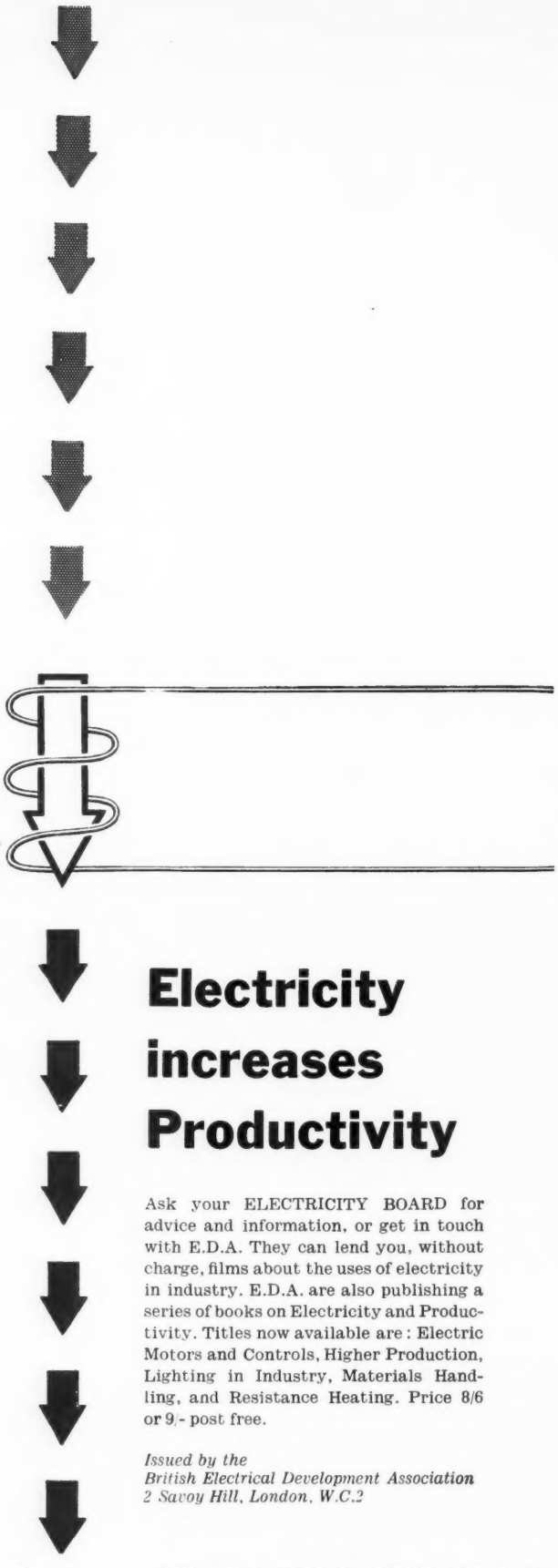

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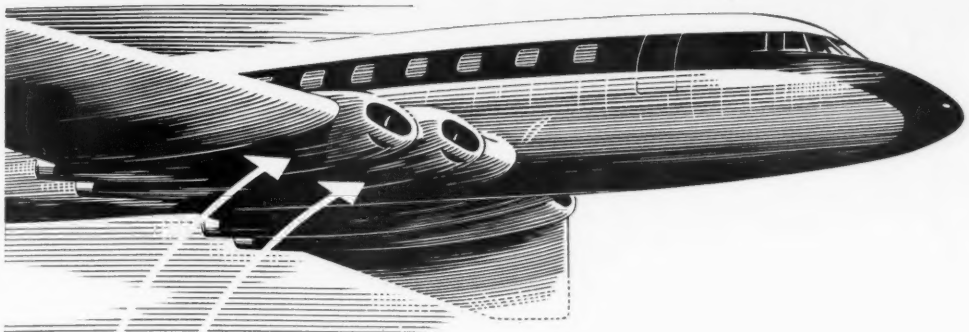

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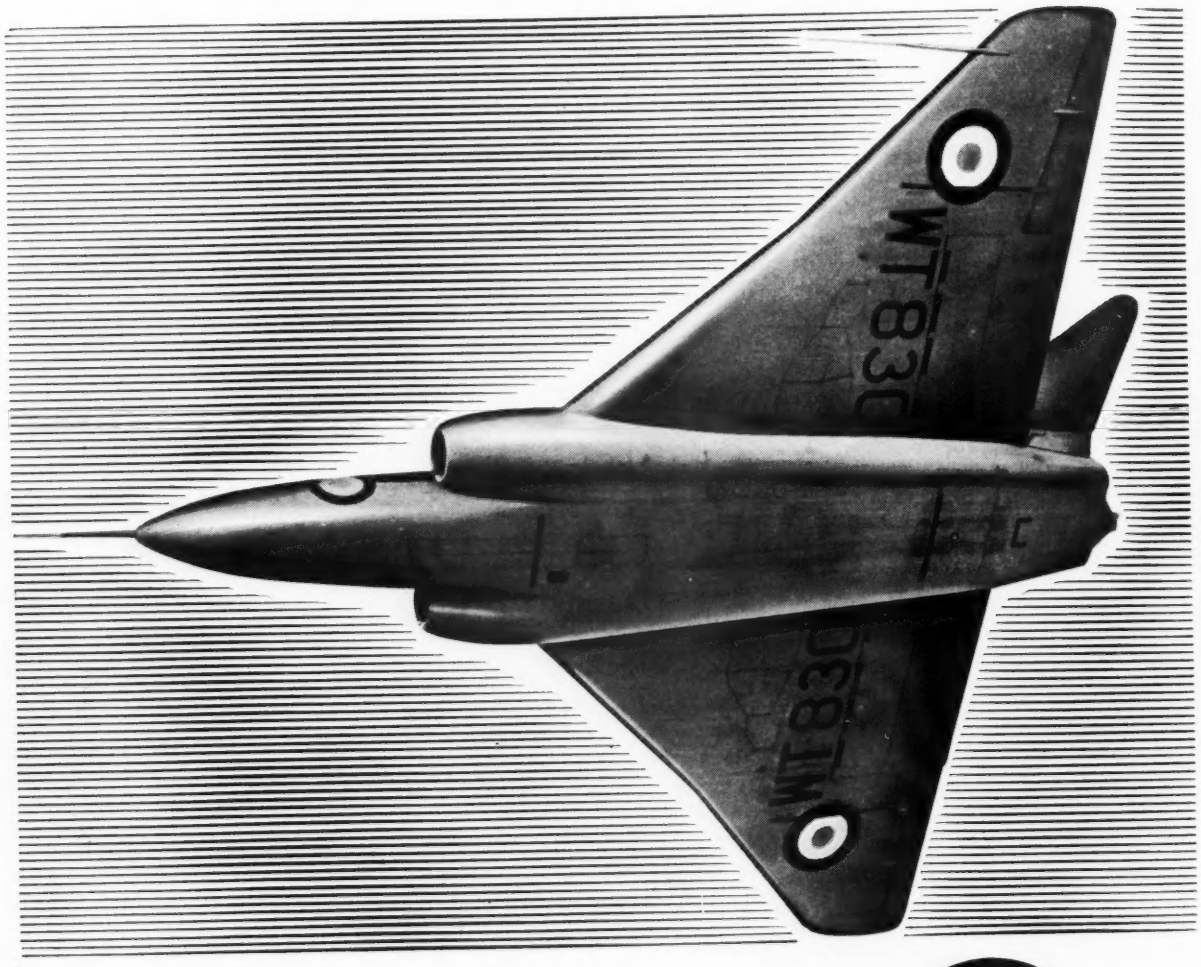

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ADDITIONS TO THE LIBRARY. REPORTS.

All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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Mr. E. T. Jones

President 1956-57

MR. Jones has been connected with aviation throughout his career. Born on 7th January 1897 he was apprenticed in 1912 to Mechanical Engineering and in 1915 joined the Royal Flying Corps. He served as a pilot and flying instructor in the R.F.C. and the Royal Air Force until 1919 and then studied at the University of Liverpool for his Engineering Degree, which he obtained in 1922.

In 1923 he joined the Aerodynamics Department at the Royal Aircraft Establishment, Farnborough and in 1930 went to the Marine Aircraft Experimental Establishment, Felixstowe where he remained until 1938. In that year he was appointed Chief Technical Officer at the Aeroplane and Armament Experimental Establishment, Martlesham.

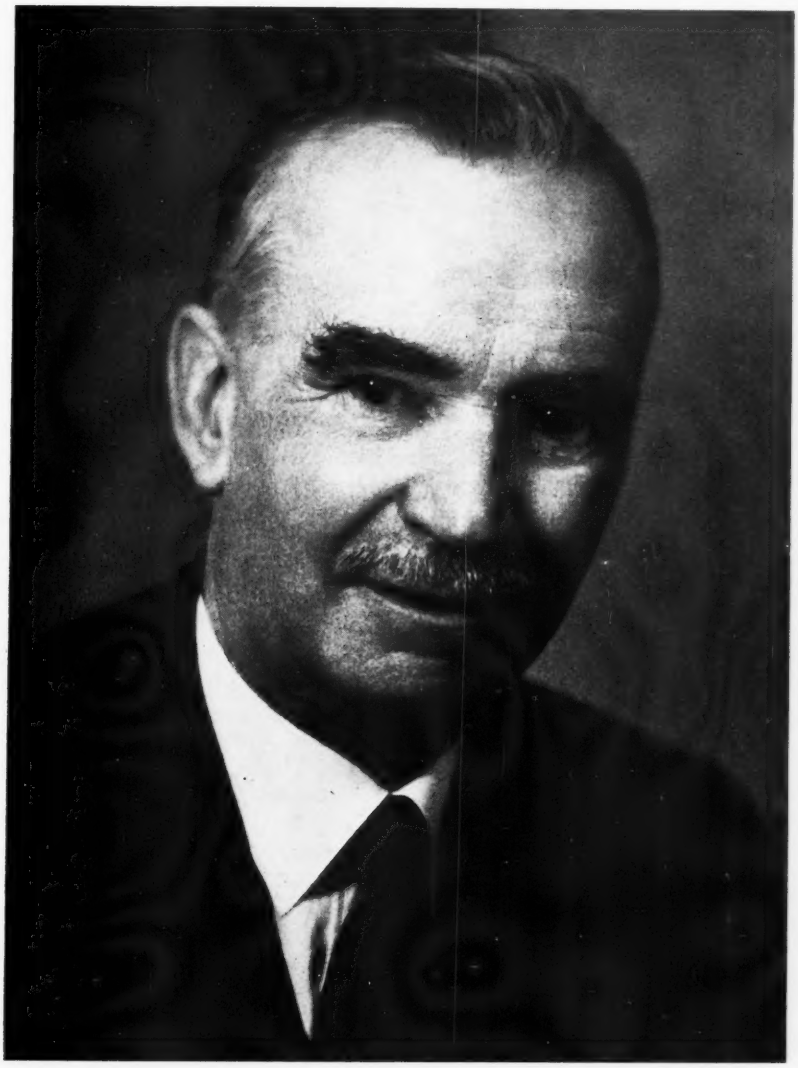
Mr. Jones was appointed Chief Superintendent of the Aeroplane and Armament Experimental Establishment at Boscombe Down in 1939, a position he held until 1947. Since 1947 he has been at the Ministry of Supply, first as Director of Instrument Research and Development and in 1949 as Principal Director of Scientific Research (Air). In 1956 he became Director-General of Technical Development (Air). He has been the main United Kingdom delegate to the Advisory Group for Aeronautical Research and Development of N.A.T.O. since its inception in 1951.

In 1942 Mr. Jones was awarded the O.B.E. and in 1953, the C.B.

He has had many Research Memoranda published by the Aeronautical Research Council and a paper on " Flight Testing Methods " published in the JOURNAL of the Society (in May 1944). He gave the Ninth Louis Blériot Lecture (which is published in this issue of the JOURNAL) in Paris on 7th March 1956.

Mr. Jones has been connected with the Society since 1936 when he joined as an Associate Fellow. He was elected a Fellow in 1944 and has been a member of the Council since 1950. He was elected a Vice-President in June 1955.

Mr. Jones takes office as President of the Society at the Annual General Meeting on 10th May 1956.



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Secretary's News Letter

May 1956.

The Council have instituted two N. E. Rowe Medals in honour of the valuable work done by the President during the years when he was Chairman of the Branches Committee. The rules for these awards are: —

1. One Medal to be awarded for the best lecture given before any Branch of the Society by a member of a Branch who is under the age of twenty-one years; the other Medal to be awarded for the best lecture given before any Branch of the Society by a member of a Branch who is over twenty-one years but less than twenty-six years old. These Medals to be awarded only if there is, in each class, a lecture which is of sufficient merit.
2. The Medals to be known as the N. E. Rowe Medals.
3. Each Branch to be able to submit not more than one entry for each Medal, to be received by the Society not later than 31st May in each year, together with an assessment by the Branch Committee of the delivery and presentation at the time when it was given.
4. The lecture(s) to be on any aeronautical subject and to be delivered within a period of thirty minutes.
5. The lectures in each class, chosen by the Branches Committee as the most suitable, to be delivered before an audience of the Graduates' and Students' Section and representatives of the Council; the latter, if necessary, will make a final adjudication.

It has been decided that the medals will have the same design on the face as the other Society medals, and on the obverse they will have inscribed "N. E. Rowe Medal. Presented by the Royal Aeronautical Society." They will be made in bronze.

Mention has been made in the Annual Report of the foundation of an Educational Fund, from which Grants may be made for various educational purposes, including fees, apparatus and books. They may also be used to supplement a scholarship, which is not, in itself, adequate to meet the needs of the student.

The Society administers three scholarships, the Charter, the Edward Busk Memorial Scholarship and The Geoffrey de Havilland Memorial Scholarship. These are now worth £50 per annum, but can be supplemented, if necessary, by a Grant from the Educational Fund.

The Scholarships are intended to assist graduates (or those who have reached graduate standard) who are engaged in theoretical or practical Aeronautical Research to undertake advanced study in the field in which they are engaged.

All applications for these Scholarships should be made before the 15th June.

The Air Transport Course which was held at Christ Church, Oxford, from the 4th-18th April was a great success and it is hoped to publish a full account of it later.

A. M. Ballantyne

Secretary

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Annual General Meeting, 10th May 1956

Notice is hereby given that the Annual General Meeting of The Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday 10th May at 5.30 p.m. in the offices of the Society, 4 Hamilton Place, London, W.1.

Associate Fellowship Examinations

The Associate Fellowship Examinations in the Old and Revised Syllabus will be held in the offices of the Society on 5th, 6th and 7th June 1956. Full particulars will be sent direct to all Candidates. June 1956 and December 1956 will be the last occasions on which Part II of the old Syllabus will be in operation.

Graduates' and Students' Section—Visits

The visit which had been arranged to the United States Third Air Force at the R.A.F. Station, Manston, Kent, for 19th May 1956 has been **cancelled.** It is hoped that it will be possible to visit the Station later this year.

A visit has been arranged to the workshops and test departments of Handley Page Ltd. at Radlett, Herts, on Saturday 9th June 1956. Applications should be made by **16th May 1956,** stating grade of membership and nationality to the Hon. Visits Secretary, Mr. N. K. Benson 14 Wakering Road, Barking, Essex.

Lecture in Paris—7th June 1956

Lieut.-General Sir John Evetts, C.B., C.B.E., M.C., will lecture to the Association Française des Ingénieurs et Techniciens de l'Aéronautiques in Paris on 7th June 1956 at 8.45 p.m. on "Woomera—Centre Anglo-Australien Essais d'Engins Speciaux" at the Société des Anciens Elèves des Ecoles d'Arts et Metiers, 9bis, Avenue d'Iena, Paris, 16e.

Members of the Society are very welcome to attend this lecture and it would help A.F.I.T.A. to estimate the number attending if those intending to do so would inform the Secretary of the Society.

Ballooning

A summary of ballooning history and a discussion on the scientific uses of balloons today will be given before the Institute of Navigation on 16th May 1956. The speakers will be C. H. Gibbs-Smith (*Companion*) and D. N. Harrison and C. S. Durst, both of the Meteorological Office. The meeting will be held at 5 p.m. (tea at 4.30 p.m.) at the Royal Geographical Society, 1 Kensington Gore, London, S.W.7.

Garden Party 15th July 1956

The Society will hold a Garden Party on Sunday 15th July 1956 at the Vickers-Armstrongs Aerodrome at Wisley, Surrey. Full particulars and application forms for tickets will be sent to members within the next week or two.

Whitsun Holiday

The Library and offices of the Society will be closed for the Whitsun holiday from 5 p.m. on Friday 18th May until 9 a.m. on Tuesday 22nd May 1956.

44th Wilbur Wright Memorial Lecture

The 44th Wilbur Wright Memorial Lecture, entitled "The Aerodynamic Art" will be given by Sir William S. Farren, C.B., M.B.E., M.A., F.R.S., M.I.Mech.E., Hon.F.I.A.S., F.R.Ae.S., on Thursday 17th May 1956 at the Royal Institution, Albemarle Street, London, W.1, at 6 p.m. Tea will be served at 5.30 p.m.

Joint Conference with the Institute of Physics

A Joint Conference of the Royal Aeronautical Society and the Stress Analysis Group of the Institute of Physics is to be held at the College of Aeronautics, Cranfield, on 19th, 20th and 21st September 1956.

Among the many subjects to be discussed are: Kinetic heating, Stresses due to jet efflux, Extensometry, Instrumentation, Crack propagation.

Further details and the full programme will be available shortly. Anyone interested in the Conference should apply to the Secretary, Institute of Physics, 47 Belgrave Square, London, S.W.1.

Acknowledgments

The Council acknowledge with grateful thanks the gift of a very fine model of the Short biplane of 1911 from Short Brothers and Harland Ltd. They also thank Mrs. S. Bell for a large collection of books, journals and photographs from the library of her late husband, John Bell, *Associate*, and Miss A. D. Betts, *Companion*, for back numbers of the Journal.

The First Minta Martin Lecture

The first Minta Martin Lecture in aeronautical engineering at the Massachusetts Institute of Technology was given on 22nd March 1956 by Dr. W. R. Hawthorne (*Fellow*), First Hunsaker Professor of Aeronautical Engineering at M.I.T. The late Glenn L. Martin endowed the Minta Martin Lecture, named after his mother, for its presentation each year in several aeronautical centres by the Hunsaker Professor. This year's lecture was on "The Aerodynamics of Aircraft Engines." Dr. Hawthorne is on leave from Cambridge University where he holds the Applied Thermodynamics Professorship.

DIARY

LONDON

9th May

ALL-DAY SECTION DISCUSSION ON SUPERSONIC FLIGHT.—Four papers introducing some of the general problems of supersonic flight will be presented by A. V. Cleaver, P. J. Duncton, D. J. Farrar and H. H. Gardner. The Institution of Civil Engineers, Gt. George Street, London, S.W.1. 10 a.m.

15th May

SECTION LECTURE.—Medical Aspects of Flight Comfort and Efficiency. Dr. A. Buchanan Barbour, O.B.E. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

17th May

THE 44TH WILBUR WRIGHT MEMORIAL LECTURE.—The Aerodynamic Art. Sir William S. Farren, C.B., M.B.E. The Royal Institution, Albemarle Street, London, W.1. 6 p.m. (Tea 5.30 p.m.).

GRADUATES' AND STUDENTS' SECTION

10th May

Some Thoughts on Present Day Aircraft and the Future. Sir Frederick Handley Page. The Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

19th May

Cancelled—The Visit to United States Third Air Force at R.A.F., Manston, has been cancelled.

9th June

Visit to workshops and test departments of Handley Page Ltd. at Radlett, Herts.

BRANCHES

9th May

Weybridge.—Annual General Meeting. Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

11th May

Birmingham.—Radar and Kindred Pilot Aids. The Birmingham Engineering Centre, Stephenson Place. 7.30 p.m.

14th May

Halton.—Film. Branch Hut, R.A.F., Halton. 6.45 p.m.

16th May

Glasgow.—Soaring Flight. A. H. Yates. Royal Technical College, Glasgow. 7.15 p.m.

28th May

Halton.—Film. Branch Hut, R.A.F., Halton. 6.45 p.m.

THE LIBRARY AND HISTORICAL MATERIAL

The addition of something like a hundred books and pamphlets from the collection of the late John Bell serves to show that, while our Library is one of the finest historical aeronautical collections in the country, there are still many gaps. A notable "find," for instance, was "Billy" Mitchell's "Winged Defense"—a topical book in view of the recent film on Mitchell's career. In the collection, too, were several unique photographs of "one-off" aeroplanes built in the sporting era between the wars. All this serves to emphasise that the Library is always prepared to take material in either large or small quantities in the hope that something will be found to add to the catalogue.

JOURNAL PREMIUM AWARDS

The following Premium Awards have been made for Papers and Technical Notes published in the JOURNAL in 1955:—

MR. G. H. LEE for his paper The Aerodynamic and Aeroelastic Characteristics of the Crescent Wing. (January 1955 Journal.)

MR. P. G. MASEFIELD for his paper Some Problems and Prospects in Civil Air Transport. (April 1955 Journal.)

MR. H. S. RAINBOW for his paper The Design of Small Jet Engines. (April 1955 Journal.)

MR. J. LUKASIEWICZ for his paper Development of Large Intermittent Wind Tunnels. (April 1955 Journal.)

MR. H. L. COX for his paper Some Problems Associated with Stress Concentration. (August 1955 Journal.)

DR. P. B. WALKER for his paper The Structural Effects of Kinetic Heating in Supersonic Flight. (September 1955 Journal.)

MR. C. SMITH and MR. J. CROWTHER for their paper The Production of Large Forgings in Aluminium Alloys. (September 1955 Journal.)

MR. E. CHAMBERS for his paper Clear Air Turbulence and Civil Jet Operations. (September 1955 Journal.)

DR. A. H. CHILVER for his paper The Local Instability of a Simple Integral Panel. (October 1955 Journal.)

DR. R. E. D. BISHOP for his paper The Treatment of Damping Forces in Vibration Theory. (November 1955 Journal.)

LIEUT. COMMANDER F. R. J. SPEARMAN for his paper The Derivation and Use of Aerodynamic Transfer Functions of Airframes. (November 1955 Journal.)

MR. HUGH L. COX and MR. BERTRAM KLEIN for their Technical Note Buckling and Vibration of Isosceles Triangular Plates having the Two Equal Edges Clamped and the Other Edge Simply-Supported. (February 1955 Journal.)

MR. A. J. BARRETT and MISS M. E. MICHAEL for their Technical Note Generalised Stress-Strain Data for Aluminium Alloys and certain other Materials. (February 1955 Journal.)

MR. C. H. E. WARREN and MR. L. E. FRAENKEL for their Technical Note A Combination of the Quasi-Cylinder and Slender Body Theories. (April 1955 Journal.)

MR. R. S. BENSON for his Technical Note The Effect of Excess Scavenge Air on the Pressure Drop in the Cylinder of a Two-Stroke Cycle Engine during Exhaust Blowdown. (November 1955 Journal.)

MR. W. JOHNSON for his Technical Note The Effect of Curvature on the Centre of Shear. (August 1955 Journal.)

FEBRUARY 1956 JOURNAL: A CORRECTION

In the February 1956 JOURNAL in the caption to Fig. 4, on page 98, of the C.A.A.R.C. Delegates at the Arnprior Flight Research Unit, Canada, Colonel C. S. Kotze was incorrectly described as representing Canada. He was in fact representing South Africa.

News of Members

E. C. Bowyer (*Companion*) has been awarded a Paul Tissandier Diploma by the Fédèration Aéronautique Internationale for his work as Director of the S.B.A.C.

Lord Brabazon (*Hon. Fellow*) has been elected President of the Helicopter Association and succeeds Lord Douglas of Kirtleside (*Hon. Companion*) who retires in May.

L. Bridgman (*Associate*) has been awarded a Paul Tissandier Diploma by the Fédèration Aéronautique Internationale in recognition of his work as the Editor and Compiler of "Jane's All the World's Aircraft" since 1941 and Compiler since 1920.

A. C. Conolly (*Associate Fellow*) has left Avro Aircraft Ltd. at Malton, Ontario, and has joined Convair at San Diego as Design Engineer.

F. G. R. Cook (*Associate Fellow*) has been appointed Director of R.A.F. Fighter Aircraft Research and Development.

A. E. Crawford (*Associate*) has joined the Brush Crystal Co. Ltd. at Hythe, Southampton, to take charge of a new research laboratory.

W. J. Eggington (*Associate Fellow*), formerly a Section Leader in the Aerodynamics Department of Vickers-Armstrongs (Aircraft) Ltd., has been appointed Chief of Special Projects with Saunders-Roe Ltd.

L. G. Fairhurst (*Fellow*), formerly Chief Engineer of Rotol Ltd. and British Messier Ltd., has been appointed Technical Director and Chief Engineer to British Messier Ltd.

R. F. Hunt (*Associate*) has been appointed to the Board of the Dowty Group of Companies.

W. H. Lindsey (*Fellow*) has been appointed to the Board of Armstrong-Siddeley (Brockworth) Ltd.

C. J. Luby (*Associate Fellow*) has resigned his position as President, Canadian Steel Improvement Ltd., to become Assistant Managing Director of Rotol Ltd., Gloucester. Mr. Luby was a Member of Council of the Canadian Aeronautical Institute.

R. E. Mills (*Associate Fellow*) has left Bristol Aircraft Ltd., to take up a new appointment at A. V. Roe Ltd. in Manchester. Mr. Mills was Honorary Secretary of the Bristol Branch.

J. L. Nayler (*Fellow*) has retired from the Secretaryship of the Aeronautical Research Council.

P. W. Parish (*Associate Fellow*), formerly Senior Design Draughtsman, de Havilland Aircraft Co., Airspeed Division, has joined Saben, Hart and Partners Ltd., as Chief Designer, Aircraft Division.

A. H. Robinson (*Associate Fellow*) has now relinquished his commission in the Air Force and has taken up an appointment with Sir W. G. Armstrong Whitworth in their Australian Armament Division at Salisbury, Adelaide.

Wing Commander V. C. Varcoe (*Associate*) has been appointed Aviation Sales Manager at the head office of Shell-Mex B. P. Ltd.

Group Captain E. A. Whiteley (*Associate Fellow*) has been appointed a Director and General Manager of the Bristol Aeroplane (Australia) Pty. Ltd., in succession to the late Mr. C. H. Tucker.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Eric William Absolon (*from Graduate*)
Nathan Norman Budish
Ronald Sidney Capewell (*from Graduate*)
John Tresham Checketts (*from Graduate*)
David Anthony Doidge (*from Student*)
Kenneth James Boyd Dunlop (*from Associate*)
Peter Lawrence Edward Gallimore (*from Graduate*)
Digby Kenneth Harris (*from Graduate*)
Edward Henry Heinemann
Alan Sidney Henney (*from Graduate*)
Subramanyam Chenna Keshu (*from Graduate*)
Yousef Fahim Loutfy (*from Graduate*)
John Graham George Marshall (*from Graduate*)
Thomas Eric Marshall
Derek Mason (*from Associate*)
Frank Ronald Mason (*from Graduate*)
Samuel Edward Nelson (*from Graduate*)
Stephen Adams Newbigin (*from Associate*)
Joseph Robin Orbell
James John Pearson (*from Graduate*)
John Edward Barrance Perkins (*from Student*)
Rudolf Albert Schwarz
Edward Arthur Leak Simmill
Ernest Arthur Tilt
Albert Arthur Weeks (*from Graduate*)
Arthur Williams
Marcus Spencer Willmott (*from Graduate*)

Associates

Kenneth Merza Ashley
Leo Verner Boland
William Morgan Davies (*from Student*)
P. Krishna Iyer
William Sutton
Robert Desmond Ward (*from Student*)

Graduates

Harry Adlerstein
Brenda Bancroft
Joe Cox
John Downs
Anthony Howard Endley
Timothy Robert Fuller
Leonard Stephen Gore
Richard John Griffiths
Keith Gordon Hodson (*from Student*)
David Michael Lumb
Peter Montague
Malcolm Christison Muir (*from Student*)
Antony Phillip Neave Potts (*from Student*)
Francis Edward Rhodes
Edward Roger Roadnight (*from Student*)
Iqbal Shoaib (*from Student*)
Colin Edward Spedding
John Charles Stanton (*from Student*)
George Edmund Charles Williams

Students

Richard Baines
James Leslie Barnes
Peter John Beushaw
Anthony George Bright
James Douglas Burley
Peter Ian Campbell
William George Stevenson Castle
Anthony James Clarke
Frederick Barry Cooper
Guy Edward Davies
John Robert James Dovey
Joseph Stanley George Downes
Douglas Alan Drinkald
Leslie Eames
Paul Rogerson Gleave
Michael Grainger
Roger Keith Grinter
John Hale
Michael Frederick Hall
Donald Isaacs
Peter Nelson Russ Jerram
Peter Douglas Jones
Keith Spencer Laird
John Geoffrey Lodge
Timothy John Richard Longley
Jessie Marguerite Lorimer
Anthony Newman Martin
William Henry Melbourne
David Morton
Gerald Michael Moss
Alan Norman Page
David John Phillips
Brian John Richards
Peter Preston Rouse
John Michael Rowbottom
Adrian Martin Seager
Alan Ernest Sewell
Peter Leslie Stuart
George Brian Taylor
Peter Ronald Taylor
Lionel Henry Townend
David Sapwell Woodward

Companion

Rajmund Ro'wniak

Changes of Address or Appointment

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters). Grade of Membership.

New address (in block letters). Old address

New appointment—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

Journal Binding

Permanent Binding

The new prices for permanent binding of Journals are: 1955 Volume (including packing and postage) £1 0s. 0d.

Previous Volumes (including packing and postage) .. .. £1 1s. 6d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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The Ninth Louis Blériot Lecture

A Philosophy of Aeronautical Research

by

E. T. JONES, C.B., O.B.E., M.Eng., F.R.Ae.S.

(Director-General of Technical Development (Air), Ministry of Supply)

The Ninth Louis Blériot Lecture was given in Paris on 7th March 1956 under the auspices of the Association Française des Ingénieurs et Techniciens de l'Aéronautiques, by Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., Director-General Technical Development (Air), Ministry of Supply, and President-Elect of the Royal Aeronautical Society.

The Lecture was attended by the President, Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., and several members of Council of the Royal Aeronautical Society, by the Secretary, Dr. A. M. Ballantyne, T.D., B.Sc., Hon.F.C.A.I., A.F.I.A.S., A.F.R.Ae.S.; by three former British Blériot Lecturers, Air Commodore F. R. Banks, C.B., O.B.E., F.R.Ae.S., Mr. H. Knowler, F.R.Ae.S., and Mr. R. Hafner, F.R.Ae.S.; and by members of the Society and the British Aircraft Industry and by a large and distinguished French audience. M. Jules Jarry, President of A.F.I.T.A., presided at the meeting and welcomed the guests before introducing Mr. Rowe and later, Mr. Jones. Mr. Jones spoke for a few minutes in French and then his paper was read by M. Maurice Roy, Director of O.N.E.R.A., and himself a Blériot Lecturer. After the lecture a film was shown of the Rolls-Royce "Flying Bedstead."

The Lecture was followed by a Reception and cocktail party and then by a dinner attended by 150 distinguished members and guests at the Aero Club de France. Among the guests were Madame Louis Blériot and M. Henry Laforest, French Secretary of State for Air. Following the dinner, speeches were made by M. Jarry and M. Laforest, and by Air Commodore Banks, deputising for Mr. Rowe who had had to return to England, and by Mr. E. T. Jones.

"Sir, said he, you have seen but a small part of what the mechanic sciences can perform. I have been long of opinion, that, instead of the tardy conveyance of ships and chariots, man might use the swifter migration of wings; that the fields of air are open to knowledge, and that only ignorance and idleness need crawl upon the ground."

—Dr. Johnson, Rasselas, 1759.

WHAT IS THE USE OF RESEARCH?

It is alleged that to a lady who once asked, "Professor, what is the use of your discovery?" Faraday replied, "Madam, what is the use of a baby?" Discovery and research—words so nearly synonymous, words that define man's unceasing search for knowledge. It is appropriate here for an Englishman to pause and reflect that when, in Britain, the need arose to define this same search for the unknown it was to France that we had to turn to enrich our language, and those two words "research" and "discovery," now so integral a part of our habits of thought, are both in their origin French. May it not therefore also be true that it was from France that we first learned that critical and scientific attitude of mind that is the essential precursor of all discovery and research?

To the Wright Brothers their "baby" was not a discovery. It was their way of presenting to the community in a direct and obvious manner the results of prolonged scientific enquiry. To the community, however, the Wrights had made a most momentous discovery for they had found a means of flying without first climbing a mountain. Like all scientific discoveries the powered aircraft opened up vast fields of research and today, 52 years afterwards, we are proud to recite our accomplishments. Stimulated and strengthened by two World Wars the baby is growing up and the community understands very fully the foolish uses for which aircraft can be exploited—but there are wise uses too, even though they may not be so readily apparent. Man, in virtue of his long confinement to the surface of the earth, is more conscious of the clouds on the horizon than of the light beyond but, in the same way that a handful of French, Italian, Dutch, American, British and other aeronautical pioneers by research and endeavour removed the mountain barriers, could not an international organisation for aeronautical research help in due time to remove the clouds from the horizon?

The military authorities of the day could not see that the work of the Wrights, and their colleagues abroad, would ever be of use in military operations and thanks to this blindness the news of the event was freely and quickly spread round the world. There followed a free exchange of information for at least a decade between workers in all countries. How strange at first glance this seems today when Governments are the sponsors of nearly all aeronautical research, custodians of aeronautical scientific capital and arbiters in the release of knowledge to the communities of the world. It is, however, perhaps not quite so strange when we realise that it is those very advances in the science of aeronautics that have made this change of outlook necessary. Nevertheless, we of the Association Française des Ingènieurs et Téchniciens Aéronautiques, the Royal Aeronautical Society, the Institute of the Aeronautical Sciences and others engaged in the promotion of aeronautics, cannot retrieve the advantages of the free exchange of the good old days by going backwards, so we must examine whether we can recapture them in the process of still further advancement.

Research is as old as man himself, but aeronautics is still new, very new, and we have a long way to go; the conquest of the air, and of space, may never be fully achieved. There can be no doubt that the second 50 years of powered flight holds a challenge more forbidding, though no less interesting, than the first but the success achieved will not be measured by man landing on the moon but by whether in the process we have learned wisdom and in doing so have restored the free exchange of knowledge within and between all communities on the surface of the earth.

Aeronautics of Yesterday

Aeronautics, as the etymology of the word implies, includes everything concerned with aerial navigation; it includes the study and charting of the atmosphere, the science and practice of navigating all forms of aircraft, both heavier- and lighter-than-air and the construction of aircraft.

Yesterday aeronautics was generally considered to embrace only the subjects of aerodynamics, structures, internal combustion engines and propellers and the technique of aircraft design and manufacture. Consequently, today the members of the older aeronautical societies and institutions of the world are mostly people who have experience in those fields, indeed the majority of the members of those bodies do not have experience outside these fields. Thus, such societies and institutions are in danger of becoming onlookers to new fields of aeronautical progress, rather than its leaders and promoters. We have already witnessed the birth and growth of supplementary societies and institutions covering such specialised fields as helicopters or rotating wing aircraft, rockets, astro-nautical navigation and so on, and while new people for new things is possibly a good philosophy, it was certainly not in the minds of those who founded the Royal Aeronautical Society of Great Britain some 35 years before the advent of the Wright aircraft that the initiative to stimulate the development of new vehicles of flight be lost.

On several occasions eminent aeronautical people have predicted a limit in the speed which aircraft could attain, but the introduction in turn of the monoplane, the retractable undercarriage and the constant speed propeller, made those predictions invalid. More recently the compressibility drag rise became known as the "sonic barrier," but the flimsiness of this barrier also was soon demonstrated with the advent of the turbo-jet and later, the rocket engine. Although it would be wrong to imply that in those days little research was undertaken by the aircraft and engine industries of the world, it is, I think, true that no firm had a large technical or scientific staff, nor possessed large-scale capital equipment capable of simulating the flight of complete aircraft. There was little electronic equipment, either in the aircraft or the laboratory, and the computing machines and telemetry equipment were respectively mainly human beings and elementary rigs. Indeed there was no need for doing these things differently since each successive era of aircraft achieved but a slight advance in speed, range or height over its predecessor and the industry found that it was able to design the new aircraft by rule of thumb methods supported by the flight experience of the preceding era.

Aeronautics of Today

Sir Harry Garner in the Fortieth Wilbur Wright Lecture to the Royal Aeronautical Society in 1952 said he doubted whether the aircraft industry today could make a great improvement on the Wright Brothers' aircraft if they were restricted to the use of the same materials and to the same stalling speed. To the metallurgist and the chemist, who seldom get the credit in aeronautics they deserve, this statement must have given great encouragement, but to the aerodynamicist, who thinks of Mach numbers in double figures, to the engine man, who thinks of thrust in tons, and to the structural engineer who has chopped a large percentage from the structure weight, such a statement, to say the least, must have appeared contentious. However, whatever the facts the moral to which they point is clear. That great advances in aero engines, in aerodynamics and in structures have been registered no one will deny, yet the engine man experiences a form of thrust reversal when he is reminded that the glider has attained an altitude two-thirds as great as the most powerful operational aircraft in the world and the aerodynamicist becomes thoughtful and relaxed when seeing in flight and for the first time the Rolls-Royce "Flying Bedstead" and realises how little his science has contributed. Unlike the engine man, the structures man glows with pride on seeing the glider though he, in his turn, ponders over the highly stressed members and redundancies in an aircraft wing when he sees the great spread of the wings of the Albatross and realises the number of oscillations under load performed by them without sign of structural fatigue. The conclusion must be that while materials have helped considerably in forging the key to aeronautical progress, the need for better materials would not have been recognised nor pursued but for the advances made by the aerodynamicist, the structural engineer and the propulsion

engineer. It has been said that no scientific discovery has ever been made which did not reveal the lack of materials for its development and the powered aircraft is no exception to this rule. Discovery leads to research and research to further discovery; such is science, first one thing leads, then another, but in retrospect all advance.

The aeronautical sciences today embrace all branches of physics, chemistry, mathematics, meteorology, navigation and human engineering and the many forms of vehicle that can now be made to take the air are apparently unlimited; the rocket which has already penetrated into space and attained a Mach number approaching double figures, the unmanned aircraft and guided weapon which can travel at high speed and navigate automatically, all could only be developed with the combined resources of an all-embracing science.

Each successive group of contemporary aircraft is a great advance on its predecessor in one operational feature or another, irrespective of whether we think in terms of military or civil requirements, and although the flight behaviour of the preceding era feeds a lot of knowledge into the pool, the gap in performance is now too great for rule of thumb methods of design to be employed and more basic research, more mathematical analyses and more laboratory work than hitherto must be done. For example, the aeroelastic problems of current aircraft are so great that some firms employ more staff on this subject alone than they did "yesterday" in the design of complete aircraft. Today firms require very expensive high speed wind tunnels, vast supplies of air under pressure, for the development of engines, ground emplacements of massive proportions for the static testing of rocket motors, computing machines capable of many degrees of freedom, ground and air telemetry equipment and electronic apparatus for the simulation of many problems, together with a vast staff of scientists, technicians and engineers to operate all this equipment.

Scientific manpower in Government aeronautical establishments is today very large and the increase is due mainly to two factors: in the first place the greater number of scientific problems to be investigated are more economically tackled by a centralised group of scientists rather than by smaller groups in different agencies of the aeronautical industry and, secondly, some of the capital equipment necessary today costs so many millions of pounds sterling that the cost would be prohibitive were each agency in the industry to provide its own.

Aeronautics (Astronautics) of Tomorrow

Although time is eternal, knowledge will die with mankind but, so long as man continues on this earth, the science of aeronautics will extend its frontiers farther and farther towards the infinity of space. In past days many limits have been predicted beyond which aircraft would not advance; time has proved them false and it is significant that today no one is rash enough to put a term to future progress and that in itself is an indication of our hopes for tomorrow. Nevertheless, there is a lot to be done before the manned aircraft can circumnavigate the earth without refuelling or landing on it; before precise navigation in space can be assured and a safe return through the atmosphere can be made following such flights; before man can even be certain of life while there. We shall need more information on solar radiation and geophysical phenomena and there are also problems as yet unknown to us and these problems, together with those which are already known, will give rise to much basic research in all the sciences known to man.

The application of nuclear power to aircraft may well be needed before the range of powered aircraft can be substantially increased. The conquest of heat will need to be achieved before we can fully realise the conquest of space. To be able to control the release of fusion energy as we can now control the release of fission energy, would make easier many future aeronautical problems and it is interesting to note that Dr. Homi J. Bhabha, the Chairman of the International Conference on the Peaceful Uses of Atomic Energy at Geneva in August 1955 stated that he expected that the scientist would be able to effect such control in about 25 years time.

Unmanned satellites will precede manned spaceships and the world has already been informed when the United States and Russia propose to launch small satellites to revolve round the earth. The Royal Society of the United Kingdom has also made its programme known and it is probable that other countries have similar work proceeding. The knowledge is already available and the necessary techniques developed and no particular difficulty is expected while such vehicles are uninhabited. The next step will be the manned satellite and the development of this vehicle will be much more difficult since the passenger will need to have at least a sporting chance of returning alive to the earth. Although many scientific data will be obtained from an orbiting unmanned satellite, and the prestige of the community that has developed it and put it into space will be greatly enhanced, the advance registered will be less real than that achieved by the succeeding vehicle which can navigate and contain men. A word of warning is probably not out of place here to those who would replace the human being by the so-called electronic brain, although an example to illustrate this point from much nearer home may perhaps better be used. Let us recall again the wonderful achievements of the glider; earlier we recognised the contributions which the metallurgist, the chemist, the aerodynamicist, the mathematician and the engineer have made but it is worth while reflecting on the achievements the vehicle itself could attain without the inclusion of man. To conceive automatic equipment which could detect electronically, or by any other means, the elements of the local structure of the atmosphere to the extent that the human being has proved he can do, is impossible while we remain ignorant of some of the input signals man automatically uses but cannot precisely describe. Man's flexible brain, together with the precise data which instrumentation can provide, form between them an integrated control which neither alone can achieve.

We might define the aeronautics of yesterday as the subsonic era, today as the supersonic era and tomorrow the hypersonic era, but at any one subsequent point of time all types of vehicles represented by these eras will be required to meet the needs of man. There can therefore be no letting up on the solution of problems at low speed merely because the way is clear for flight at supersonic or hypersonic speeds, no letting up on the problems of economic operation and safety of passenger-carrying aircraft, and no letting up on the many lines of research to evolve non-inflammable materials. On the contrary, we must ensure that today's problems are not eclipsed by tomorrow's prospects; we must make aircraft safer and safer as well as faster, farther and higher and this demands, in the ultimate, aircraft which can land in any weather without forward speed. The aeronautical problems of the future are therefore immense.

The Impact of Aeronautics on the Communities of the World

It would be difficult to imagine life today without the wheel—without the millions of them we see every day—yet since its early days the wheel was put to deadly purpose in war and sometimes, alas, in peace as well. Today we recognise only the benefit mankind derives from the wheel and not least among these is the speed of communications the wheel has made possible. History will in due course record the part aeronautics has played in bringing the communities of the world closer together, not merely in time but closer in thought and understanding, and it is sufficient here only to remark that it is we who are engaged in the science of aeronautics who can set the course for history to follow. The aeronautical science, like the wheel, will be used for purposes other than speeding up communications and its greatest use to mankind will not be the speed of the developed vehicles as such, but the smoothing influence their presence will have on the communities of the world. Unlike the wheel which is earth-bound, aerial vehicles can navigate a three-dimensional course and this renders the science of aeronautics unique. These vehicles will, in due course, provide a physical link between the earth and other parts of the universe and not until then will man be able fully to appreciate his proper status.

There are 87 countries in the world, some are small and some we consider large; some are densely populated and some thinly; some we call major powers and some minor powers but, in due course, how insignificant they will all appear and how minor will their differences seem when viewed from the moon by a representative party of one individual from each of them. There are some who would delay the launching of satellites, spaceships, and so on, in the belief that man may get to know more than is good for him, but man already knows more than is good for mankind and not until he knows still more will he be able to adapt what he knows to the benefit of mankind as a whole. It is generally recognised that when a community is in a state of turmoil the best way to restore tranquility is to give the people something to do together or something new to talk and think about. Man-launched satellites will at least provide a new and universal interest; they will be there for all to see and marvel at and they will be unique in that while in space they will cease to belong only to the particular country of their origin.

On our way back to earth let us survey the part aeronautics is currently playing to bring communities closer together. First, anyone who has travelled much by air is immediately impressed by the ease of world travel—a booking anywhere to anywhere can be made in one's own home town, even though it may involve journeys over many different countries and on many different airlines and travellers often do not realise the international nature of that body, the International Air Transport Association, which has put in such hard work to make this state of affairs possible. The most lasting impression, and the most important, is the friendliness of all peoples of the world and the fact that one can meet more people of other nations in one year than can be met in a lifetime using other forms of travel. The International Civil Aviation Organisation is a body having 63 different countries represented on its Council, which, among other things, promulgates the codes of practice which have been adopted by most of the airlines of the world. The aeronautical societies of France, the United States of America and Great Britain have among their members people from many different countries. The Royal Aeronautical Society prepares and publishes Data Sheets on aerodynamics, structures and performance and these are purchased by no fewer than 50 different countries. Among the civil airlines Air France advertises "45,000 departures every year; every 12 minutes an Air France aircraft takes off somewhere in the world." Holland's K.L.M. "Links 100 cities and penetrates 67 countries," "B.O.A.C. flies to 51 countries on all six continents"; Australia's Overseas Airline "Links 26 countries and 5 continents"; the airlines of Italy, Canada and the United States of America advertise similar world services. Many of these airline Corporations operate with aircraft made in countries other than their own and the air crews are at home in any and every country of the world. Such, even today, is the flexibility of aircraft operations, or to express it in another way the air on which they ride is "standard gauge" the world over, and the same codes of practice obtain throughout, in fact aircraft design and operation is to a first approximation independent of the habits and customs of any particular community. In other words the popular cliché that aeronautics is making the world smaller is true; it is sweeping away boundary fences and reducing local habits and customs to a common denominator.

Yesterday aeronautics was exploited because of its potential in war, today it is exploited because of its potential as a deterrent to war and tomorrow we hope it will be exploited because of its potential as an explorer, philosopher and communal friend. This then is the background to any future programme of aeronautical research.

Scientific Capital and its Creation

In his book "Human Knowledge" Bertrand Russell says, "The community knows both more and less than the individual; it knows, in its collective capacity, all the contents of the Encyclopedia and all the contributions to the Proceedings of Learned Bodies but it does not know the warm and intimate things that make up the colour and texture of a human life." In extrapolation of this profound yet simple statement one might say that, despite the numerous scientific societies and periodicals which disseminate scientific information, there are varying degrees of intellect and intent between nations and therefore there are two frontiers of knowledge. There is the frontier common to all nations and there is superimposed on this the frontier peculiar to an individual nation. Ideally, and in stable peace conditions the significance of the phrase "more and less" in the above context should be small, but in war it could be prodigious.

Scientific capital is the fund of scientific knowledge possessed by a nation and it is this fund of knowledge which forms the foundation on which new techniques and processes are built; although a high individual and high collective intellect of a community are valuable assets they are not in themselves sufficient to ensure that the rate at which a nation is accumulating scientific knowledge is comparable with that of other nations. The Government must assist educational institutions to foster a scientific outlook and it must encourage the formation of learned societies; industry must provide the environment and opportunity which will attract those who are best equipped for, and prepared to pursue, the quest of scientific knowledge and there must be adequate machinery for the dissemination of that knowledge within the community and organisations to extract, receive and collate the knowledge available, and currently becoming available, by the communities of other nations. Thus the onus for knowing where the frontiers of knowledge are, or the amount of scientific capital available at any time and for adding to this capital, is shared by the individual, the educational and scientific institutions, industry and the nation as a whole. In practice the frontiers of knowledge are continually being advanced by the combined efforts of universities, research groups and industrial organisations, research establishments sponsored by Governments and by individual scientists in all parts of the world.

Scientific knowledge does not advance on all fronts simultaneously but an advance on one front invariably, and often quickly, leads to an advance on other fronts. A new chemical will set up a chain reaction of events, a new fuel may revolutionise the cost of the generation and availability of power, a new process for the production of a material may change completely an engineering structure and further study of the sun's ultra-violet emission may lead to long-term weather forecasting and, in turn, to a partial control of the weather. It is perhaps unfortunate that a partial understanding of nuclear physics has led to the atomic bomb as well as to radio isotopes, but a more complete understanding may well lead to the antidote for the atom bomb. In our limited wisdom it seems that there is no present way of exploiting the available knowledge to the ultimate good of mankind rather than for merely destructive purposes, or to ensure that the technical effort available is so fully employed in exploiting scientific capital for the benefit of mankind that no effort remains for subversive aims. But who would then dare to be the arbiter of good and evil and at what point in time could a right judgment be made; the question "What is truth?" has remained unanswered down the ages. The philosopher's cry that life is one vast illusion is probably the most concise and cogent reason why the unceasing and uninhibited search for knowledge must continue.

Knowledge without skill to apply it, to make something new or better or more economical, is merely academic and it is academic too to think of science and research merely as the accumulation of knowledge without the application of that knowledge to the needs of tomorrow—the applied research that is in fact development and production. There is today more science in the fabrication of material for the economic production of a complicated article than was employed in many of the classical laboratories of the past.

Although aeronautics embraces all the sciences known to man it is not in itself a basic science and progress in aeronautics by no means depends solely on the progress made by those engaged in the advancement of aeronautics. We have seen that the metallurgist working in the research department of the heavy steel industry may produce an alloy which, when processed by the aeronautical engineer, may affect considerably future generations of aircraft. The chemist too or the classical physicist working in a university may provide the knowledge which the aeronautical worker will integrate for his specialised field. On the other hand, radar, which was first evolved to meet the needs of aeronautics, has been processed to many other non-aeronautical uses. Louis Blériot in 1909 and Alcock and Brown in 1919, by virtue of their outstanding flights, both provided a spur to further progress in fundamental science by showing the potentialities of aircraft in linking countries and continents in ways that heretofore had been merely the poets' dream.

The scientific capital available for exploitation in the aeronautical sciences is bounded by two frontiers, the frontier of knowledge amassed by scientists working in all fields and, superimposed on this, an advanced frontier of knowledge in the specialised aeronautical field. The mathematician had an understanding of fluid motion long before the advent of aircraft and he would have added gradually to this knowledge even though aeronautics had not been born but, because aeronautics necessitated a great increase of knowledge in that field and in the derivative field of aerodynamics, the subject of fluid motion has attracted some of the best qualified people in the world and, despite the enormous effort devoted to the subject over the past 50 years, we still find today that more theses from aspiring doctors of philosophy are submitted on fluid motion than on any other subject associated with the aeronautical sciences.

Research and the Community

In the history of every nation giants of research and invention have appeared and these relatively few people have led to life as we know it today. Similarly, tomorrow's way of life is being moulded today in the research laboratories of the world but the tempo of life in the past is likely to rise in the future with ever-increasing acceleration. Man has occupied the earth for at least 200,000 years, yet it is only during the last century that the fruits of research and invention have been made available to all and sundry as part of their way of life. A hundred years or so ago there was no large scale use of mechanical or electrical power and communications both within a community and between communities were slow and laborious, but the advent of power on a large scale has revolutionised life in every country in which it has been introduced and in so doing has stimulated research and the urge for progress.

Before the advent of power there was little industrial development and no machines capable of the mass production of commodities. In those days, therefore, research was largely academic with little prospect of commercial exploitation. The research worker was in consequence practically unknown in industry and, except for the giants, was a lone worker, poorly paid, if paid at all, of lowly status and without business acumen; he was a curiosity both to the general public and to the masters of industry. This early attitude of mind probably explains why even today the unthinking consider all forms of research to be a purely individual idiosyncrasy, far removed from the practical business of manufacturing and developing, not comparable with the practice of the arts and of far less importance than administration—a thing that their sons and daughters should avoid at all costs.

Fortunately, however, this somewhat supercilious attitude is rapidly changing and it is becoming widely recognised that the research of today determines the way of life of tomorrow, that those who neglect research in their industry will destroy their heritage and that the qualities needed for a good research worker are not unlike those necessary for a good business executive. It is gradually being recognised that the doors of the Board room must be open to the man of science and that research into the whole range of technical processes and of production methods, too, will become more and more essential the greater the installed power of a country becomes. It was not chance that the growth of production in the United States of America coincided with the introduction of scientific and technical people into managerial posts in industry, nor was it bad luck that the apparent prosperity enjoyed by the United Kingdom through industrialisation in the Victorian era was not consolidated. We know now that it was due to the failure of the community to recognise that industrial prosperity could not survive without adequate scientific and technical support both in the works and in the management.

Research, development and production can be considered as one integrated chain reaction; at one end is fundamental or basic research and at the other a new commodity or service for distribution to the community. Before the industrial era the term "research" was generally understood to relate to work in one or other of the sciences completely divorced from any commercial application, what today is termed basic research and for which the environment of a university was and still is acclaimed supreme. Today we realise that research is essential to the development of the technical and engineering techniques to exploit this basic knowledge, that applied research is a necessary part of all our technical and industrial endeavours. Last, but by no means least, is the problem of production and of the research associated with it; the need is constantly growing and it must be met if we are to survive. This can only be done by increasing the percentage of the community educated in science and technology and the emphasis at schools and universities on these subjects must be increased. That policy is more difficult to implement in the long-established communities with inborn traditions and prejudices than in relatively newer communities, but failure now to appreciate that yesterday's educational system is outmoded by today's needs will surely lead to disaster tomorrow.

Europe has for centuries been in the forefront in the creation of scientific capital but it is significant that it was left to the United States of America, a relatively new country, to show that research had a much wider meaning in modern life than the purely academic; on the other hand it is noteworthy that the most progressive of European industries, such as the chemical industry, were among the first to create large research departments and to utilise to the full the scientifically trained man at all levels.

Aeronautical Research and the Community

If, as has been said, aeronautical engineering is ordinary engineering made more difficult it is equally true that aeronautical research is ordinary research made more expensive. Indeed, although the whole encyclopedia of "ordinary" science is needed somewhere or other in the design, development, production or operation of aircraft, the aeronautical scientist must add to every section of it knowledge and skill peculiar to his own needs. All that can be said in support of non-aeronautical research and its concomitant industry can be said with greater emphasis about aeronautical research and the aeronautical industry; both need more scientists, more technical staff and more facilities, but there are additional factors to be noted and some are unique to the aeronautical field.

Aeronautical research is destined to become, like the Arts and the practice of medicine, a communal subject: a subject to integrate communities and, like metaphysics and astronomy, one to be studied and progressed collectively without national restrictions by all communities. In due course it will be raised to where it belongs—to the sky—and away from all international disturbances but, with such a future, it is ironical to find that there is throughout the world more duplication of effort and of individual capital facilities connected with aeronautics

than with any other of the sciences. There is an explanation, though possibly not an excuse, for this when it is realised that, although much basic research is conducted with small scale and inexpensive equipment, there still remains much that can only be done with extremely expensive capital facilities requiring large power supplies and a large scientific staff to operate. The development of vehicles for flight requires much applied research in structures, electronics, propulsion and aerodynamics and in consequence each firm in all the associated industries needs large and costly facilities with large scientific and technical staffs and, in addition, the flight testing of the vehicles requires elaborate airborne and ground facilities and large technical staffs to control the programme of flight tests and to arrange for the reduction of all the data from the tests and all these facilities are also duplicated, to a greater or lesser extent, in many nations. The Southern California Co-operative Wind Tunnel, which now serves five major United States aircraft companies, and the Aircraft Research Association tunnel of the British Aircraft Constructors now being built, are examples of co-operation which might well be followed in a broad way, and it is interesting to note that the French aeronautical authorities are currently discussing with other European countries the advantages of co-operative aeronautic facilities.

Because of the military uses to which aircraft can be put and the rapidity of advance which is now possible, national security requirements have made it necessary for individual nations to erect and maintain large Government research and experimental establishments and to employ large numbers of scientific staff in addition to those engaged on research in civil research institutions, universities and in industry. No other field of science, with the possible exception of nuclear physics, requires such gigantic and costly capital facilities as those nationally owned and used exclusively for the advancement of aeronautics.

At present national security operates against the free dissemination of aeronautical scientific knowledge and this means in effect that any nation wishing to keep abreast with others must create its own scientific capital.

Finally, we must not lose sight of the time scale necessary to develop a new and sophisticated range of military aircraft, or guided missiles, or civil air liners, or ballistic rockets or even, indeed, of an orbiting satellite. Although the developed article may be small in size compared with a battleship, an ocean-going liner, a hydro-electric or nuclear power station, the problems to be overcome are so numerous and complex that the time to develop it may well be comparable, or even greater. Since, however, with the present-day rate of progress it very soon becomes obsolescent, the development time is much more critical and suitable facilities must generally be provided on the site and all suitable manpower available absorbed. For all these reasons, therefore, it is understandable that throughout the world there is greater duplication of scientific effort and of facilities for research in the aeronautical sciences than there is in any other field. There is, however, the possibility that we may now have an opportunity to redress this undesirable situation with the development of the satellite and later, the space-ship. The rocket interplanetary enthusiasts have already founded within an international organisation devoted to the promotion of space travel, 24 space flight societies, and they and similar visionaries might in due course establish that co-operation and the free interchange of ideas make duplication unnecessary.

However, we have to live in the present and today all industrial communities suffer from extreme shortages of scientific and technical manpower. Although this acute shortage has only recently made itself felt, its cure is likely to be a long-term solution and it should not be assumed that, in an expanding industry, it will right itself. On the contrary, with nuclear power well on its way we can expect that with all these recent inventions and discoveries, such as antibiotics, man-made fibres, radio and television, turbo-jets and rocket engines, pushing on each other's heels, they will in turn be followed by later inventions and discoveries in the same way that the satellite will follow the ballistic rocket, which itself in turn followed the aircraft.

It is sometimes suggested in the United Kingdom that headmasters of schools and the staff of universities should be pressed to encourage more students to take up science and technology at the expense of the arts, but this suggestion does not seem to strike at the root of the problem. The problem with all heavily industrialised communities today is not one of resolving an imaginary conflict between the humanities and science, but rather to determine a formula for blending them to produce a more balanced educational system. Such a change of emphasis between walks of life hitherto regarded as mutually exclusive would help too in reducing overlapping and duplication of duties between administrative and technical elements of industry, and also improve the prospects of able technical men who are also potential administrators. In any event we must ensure that our young scientists are not like the man possessed of the Devil whose last state was worse than his first. So easily concentration on the sciences may, through disregard of the humanities, lead to ultimate disaster. No effort must be spared to ensure that the early educational years of the future scientist are so planned that he will acquire that broad outlook and sound moral principle which is the only sure basis upon which a scientific philosophy can rest.

Organisation for Aeronautical Research

Since the community as a whole represents the potential available for research it follows that duplication of effort can only be avoided where there is free access by the community to all the frontiers of knowledge. Whenever this open access is not available there will be blind areas and in these not much research will be done. Thus in those fields of science where national security must take precedence, the frontiers of knowledge will not be widely known and the effectiveness of the community to play its full part will be reduced.

In aeronautics, unfortunately, defence needs must predominate and many of the custodians of scientific

knowledge, and indeed of those whose function it will be to exploit it, are either Government servants or are working on projects sponsored by the Government. Hence the community at large has no idea at any one point of time where the frontiers of knowledge in aeronautics are and in consequence the potential available for research is severely restricted. Advisory councils and committees, such as the United Kingdom Aeronautical Research Council, its committees, and subcommittees and the United States National Advisory Committee for Aeronautics, which have as members independent scientists, in the sense that they are not directly employed by their Governments, have the effect of making these frontiers known to a larger community. In France, while there is nothing precisely comparable with these organisations, this duty rests with the Office National d'Études et de Récherches Aéronautiques (O.N.E.R.A.) with its associated Councils and Committees in close co-operation with the "Direction Technique et Industrielle de l'Aéronautique." Through the regularly published Journal "La Recherche Aéronautique," the O.N.E.R.A. passes on to all who are interested many results of their efforts to extend the frontier of aeronautical knowledge. The Association Française des Ingénieurs et Tèchniciens Aéronautiques, too, has a system of committees and these perform a somewhat similar function to the technical committees of the Royal Aeronautical Society. In addition to such constituted bodies, in many countries symposia on selected topics are arranged at intervals to bring the latest results of scientific research to the knowledge of a wider field but, despite these arrangements, there remains a large scientific potential within the community which cannot contribute because it does not know how far a problem has been advanced and what still remains to be achieved, nor does it even know the defence research policy of its own country. It is now common knowledge that, to bridge this gap, the United States Government have introduced a system whereby groups of universities and of specially selected industrial undertakings are given aeronautical problems to solve on contract, in addition to items of more conventional research. These problems require full-time study and have the effect of educating the university and other staffs up to the level of the knowledge possessed by the official scientist. A by-product of the scheme is that it brings home to the university graduate the importance of research and probably influences many of them to adopt aeronautical science as a career.

The greater defence significance of a science the more difficult it is to keep the community informed and, the less the community is informed, the less it can contribute and consequently the less it will eventually be able to defend itself. The "point of no return" is impossible to define but there can be no doubt that today few communities would be far from this point were it not for the mature traditions of these old-established and learned societies and institutions which have for so long pressed for the publication of scientific knowledge as and when it becomes available. It is the influence and teachings of these bodies which urges the scientist to write and speak of his work and it is the combined urge of the scientists, both within and without the Government, for their work to be published which ensures that information is not held longer than security demands. On such organisations rests our hope for the future.

What is true for the organisation of research within a particular community applies with equal force to all communities within the comity of nations, although detailed arrangements may well differ. All communities have their learned societies and institutions and if all were equally effective in promoting publications, the international frontier would closely approximate to the advanced frontier of any one nation, there would then be less duplication of research effort and the need for each community to have all the large and expensive capital facilities necessary for the pursuit of a full programme of aeronautical research would consequently be reduced. It was to this end that Sir Ben Lockspeiser put forward in 1946, a suggestion subsequently endorsed by the Governments of the British Commonwealth of Nations, for the setting up of a Commonwealth Advisory Aeronautical Research Council and, although it is not unlimited in scope, it has nevertheless achieved a worthwhile integration of research. Dr. Theodore von Kármán too, working in a wider field, had the right idea when he proposed the establishment of the Advisory Group for Aeronautical Research and Development comprised largely of the aeronautical research directors of communities represented by the North Atlantic Treaty Organisation. This organisation, now five years old and well known to all N.A.T.O. countries has, mainly through the efforts of von Kármán, its present chairman, now become well established and is destined to become increasingly important. The C.A.A.R.C. and the A.G.A.R.D. are good beginnings, and so too are the Anglo-American Aeronautical Conferences, and the European Aeronautical Conference organised by the Association Française des Ingénieurs et Techniciens Aéronuatiques, but there still remains much more that must be done.

We spend our lives painfully searching for knowledge, but knowledge without wisdom will profit us nothing. Let us not forget the truth that, as one of our English poets has it:

"Knowledge, a rude unprofitable mass;
The mere materials with which wisdom builds.

Knowledge is proud that he has learn'd so much;
Wisdom is humble that he knows no more."

AIRCRAFT DESIGN PHILOSOPHY

An All-Day Section Lecture and Discussion on "Aircraft Design Philosophy" was held by the Royal Aeronautical Society on 17th November 1955 at the Institution of Civil Engineers and was presided over by Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S. Introductory papers were given by Mr. R. H. Sandifer, F.R.Ae.S., Mr. J. K. Williams, B.Sc., A.F.R.Ae.S., Mr. H. Giddings, A.F.R.Ae.S., and Dr. P. B. Walker, C.B.E., M.A., F.R.Ae.S. Each paper was followed by a Discussion and there was a general discussion at the end of the session. Mr. A. J. Barrett, M.Sc. in A.E., B.Sc.(Eng.), M.I.A.S., A.F.R.Ae.S., acted as rapporteur for the Discussions.

Flight Loads

by

R. H. SANDIFER, F.R.Ae.S.
(*Handley Page Ltd.*)

1. Historical

For centuries man has watched with envy the easy flight of birds and has tried to simulate their basic form, structural principles and methods of control. Often too much enthusiasm and too little technical knowledge has ended in disaster, and the most successful people were those who relied upon models for their initial data.

The Wright Brothers were among the first to apply an engineering approach to the problems concerning the magnitude of loads occurring on wing and control surfaces. To this end they constructed a wind tunnel as long ago as 1901[1] and succeeded in measuring actual forces on model aeroplanes, and in comparing them with systematic glider experiments. They continued to develop their research along these lines to achieve the first power flight in December 1903.

Since that date many more experiments have been conducted to measure the maximum forces which occur on various components of an aeroplane, and initially these forces served as design criteria, supplemented by generous factors of safety to cover many unknowns. Inevitably accidents occurred, and the lessons learnt were utilised to provide safer design criteria and more rational factors of safety.

This procedure continued for some years, to produce an increasing volume of data which was as yet not co-related to any serious degree.

The advent of the First World War brought about the first publication of flight load requirements in the form of a Government Publication known as H.B.806 (in 1918). Later this was superseded by A.P.970 (in 1928) for military aeroplanes and by A.P.1208 (in 1926) for civil aeroplanes.

A.P.970[2], of course, is still the official document for military aeroplanes but A.P.1208 was superseded by B.C.A.R.[3] after the Second World War (in 1945).

The earlier publications contained requirements couched in terms of loads for recognised extreme manoeuvres such as: —

C. P. Forward—Instantaneous Flight at maximum acceleration and angle of incidence.

C. P. Back—Instantaneous Flight at maximum acceleration and minimum angle of incidence.

Fast Glide at Terminal Velocity Dive—Virtually zero or minimum lift and maximum wing torque at maximum speed.

Also, somewhat arbitrary or empirical load conditions for designing control surfaces.

At this stage it is relevant and fair to point out that it was also a requirement that the aeroplane should, for each of the major conditions, be correctly balanced as a "free-free" beam under the action of aerodynamic and inertia forces.

In 1938 Dr. P. B. Walker put forward a scheme for rationalising all these stressing cases, which finally took the form of an envelope of all possible flight conditions within certain predetermined limits of speed and manoeuvre acceleration. The scheme was later published as R. & M. No. 1916[4], and provides the basis of the modern Flight Envelope.

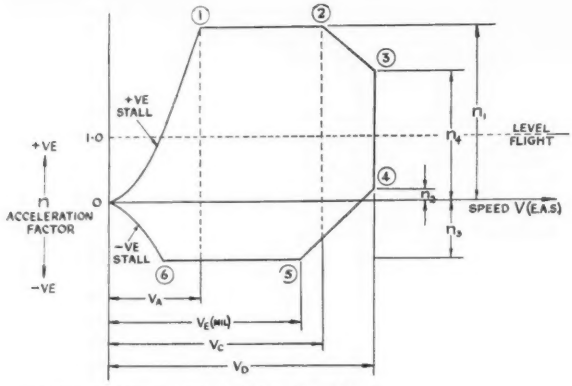
2. Current Requirements

These are constantly under review, and in what follows occasional reference will be made to requirements which are about to be published. Differences between Civil and Military requirements are often based upon the different operational duties of the respective aircraft.

2.1. FLIGHT ENVELOPE FOR SYMMETRIC MANOEUVRES

Figure 1 shows a typical envelope, as prescribed in B.C.A.R. for civil aeroplanes or, for military aeroplanes, in A.P.970. Beneath this envelope are tabulated the comparative values of normal acceleration factors called for, in terms of n_1 the maximum positive factor. Reference to Figs. 2 and 3 later will clarify the comparison.

Briefly, it will be noted that this envelope is a graph of normal acceleration factors plotted against speed, the modern basic concept being to provide a boundary of conditions to and from which the aircraft may be



COMPARATIVE ACCELERATION FACTORS.

POINTS	CIVIL	MILITARY
① & ②	n_1	n_1
④	$n_3 = 0$	$n_3 = 1-0.3n_1$
⑤ & ⑥	$n_3 = -1.0$*	$n_3 = -0.6(n_1-1)$
③	$n_4 = 0.75n_1$ or ± 2.0*	$n_4 = 0.75n_1$

*HIGHER VALUES FOR AEROBATIC CATEGORIES.

FIGURE 1. Basic flight envelope.

manoeuvred. Overall Safety Factors are then imposed on the maximum expected loads described by the envelope, and the results applied to the aeroplane as a whole. All altitudes are considered since at altitude higher Mach numbers are reached and with increase of M, a number of aerodynamic coefficients become more critical.

Points to note, regarding acceleration factors are: —

(*i*) All acceleration factors are related to the maximum positive value n_1 which is chosen to cover all reasonable manoeuvres for a given type of aircraft. In both civil and military types this choice has a background of much data from V-g records and adequate safety is maintained by adopting a statistical approach and avoiding the probability of exceeding the design value more than once in a specified number of flying hours.

(*ii*) For convenience, empirical formulae have been used to co-relate other values of n to n_1 and, although there is general agreement between civil and military results for a range of values of n_1, the civil acceleration factors appear to be a little more conservative on negative accelerations for large aircraft (*i.e.* at low n_1) (*see* Fig. 2).

(*iii*) It is also of interest to note in Fig. 3 that the ratio of positive to negative manoeuvre accelerations from level flight ($n=1$) is in fair agreement for both types, except that for high values of n_1 and at high speeds only, the civil ratio is greater than the military one; that is, the civil negative g is low or the military one is high. It is possible that the civil philosophy has become the victim of an empirical ruling here, since the military values are based on V-g records.

(*iv*) Except in some prototype aircraft, it is not general to provide the pilot with an acceleration recorder among his many instruments but to rely on his training, experience and general flight instructions to control these values. In recent years the incorporation of a g restrictor has been given serious consideration but its advantages are debatable, particularly on military aircraft where strong evasive action may have to be taken to save the aircraft from a worse fate than just "bent" wings. The compromise, to allow a bent, but not a broken structure, appears to be the solution. A point to remember, however, is that the fitting of a g restrictor does not necessarily give full protection to the tailplane.

Reverting now to Fig. 1, consider the speeds associated with the acceleration factors already noted. Since load varies as (speed)^2, the positive stall curve, *i.e.* constant angle of incidence, is represented by a parabola.

Manoeuvring Speed V_A at point (1) is therefore the highest speed at which stalling can occur within the specified maximum positive acceleration.

Cruising Speed V_C is the greatest speed at which the aeroplane may be expected to operate continuously, and is therefore associated with maximum positive acceleration (point (2)). In the civil field, a safeguard is provided against the possibility of exceeding this speed in turbulent weather by requiring V_C to be at least 50 m.p.h. E.A.S. greater than V_B, the lowest speed at which the most severe gust will not stall the aircraft. This applies up to 20,000 ft. with a proportionate reduction for air density above this height. An upper limit of $0{\cdot}9V_D$ is also specified. The military requirement for

CIVIL

n_1	2·5	3·0	3·5	4·5	6·0	
$n_2 = 0$	0	0	0	0	0	
$n_3 = -1$*	-1·0	-1·0	-1·0	-1·8	-3·0	
$n_4 = -0.75n_1$ or ± 2.0*	-2·0	-2·25	-2·63	-3·5	-4·5	
+VE MANOEUVRE $n_1-1 = a$	1·5	2·0	2·5	3·5	5·0	NORMAL SPEED RANGE
-VE MANOEUVRE $n_3+1 = b$	2·0	2·0	2·0	2·8	4·0	
a/b	0·75	1·0	1·25	1·25	1·25	
+VE MANOEUVRE $n_4-1 = c$	1·0	1·25	1·63	2·5	3·5	HIGH SPEED RANGE
-VE MANOEUVRE $1-n_2 = d$	1·0	1·0	1·0	1·0	1·0	
c/d	1·0	1·25	1·63	2·5	3·5	

*HIGHER VALUES FOR AEROBATIC CATEGORIES.

MILITARY

n_1	2·5	3·0	3·5	4·5	6·0	
$n_2 = 1-0.3n_1$	0·25	0·10	-0·05	-0·35	-1·0	
$n_3 = -0.6(n_1-1)$	-0·9	-1·2	-1·5	-2·1	-3·0	
$n_4 = -0.75n_1$	-1·88	-2·25	-2·63	-3·38	-4·5	
+VE MANOEUVRE $n_1-1 = a$	1·5	2·0	2·5	3·5	5·0	NORMAL SPEED RANGE
-VE MANOEUVRE $n_3+1 = b$	1·9	2·2	2·5	3·1	4·0	
a/b	0·79	0·91	1·0	1·13	1·25	
+VE MANOEUVRE $n_4-1 = c$	0·88	1·25	1·63	2·38	3·45	HIGH SPEED RANGE
-VE MANOEUVRE $1-n_2 = d$	0·75	0·9	1·05	1·35	2·0	
c/d	1·17	1·39	1·57	1·78	1·73	

FIGURE 2. Relative values of acceleration factors for flight envelope.

V_C is $0{\cdot}8V_D$ with increases up to V_D in special cases, and the choice is based largely on V-g records.

Diving Speed V_D is similarly to be greater than V_C by a safe margin of 70 m.p.h. above V_C (points (3) and (4)).

The general philosophy here is that military requirements are based upon years of experience and testing, and the civil requirements, while keeping one eye on this experience, have made a fundamental approach from the safety aspect of regular airline flying. To this end the airline pilot is given a Normal Operating Speed, V_{NO}, which may be slightly less than V_C but never greater. Similarly V_{NE} the "never exceed" speed is generally $0{\cdot}9V_D$. Thus there is a reasonable margin of safety to cover inadvertent, or calculated excesses under severe or abnormal conditions which, used in conjunction with weather reports, gives protection to the passengers and crew of the aircraft.

The military pilot may have to take "calculated risks" more frequently and should share with the designer the responsibility for excursions to speeds between $0{\cdot}9V_D$ and V_D. For modern high speed aircraft the top right-hand corner tends to be filled in, because cruising speeds are relatively higher. Point (5) on the flight envelope corresponds to V_C for civil aircraft but is at a somewhat lower speed for military aircraft, based on V-g records, but the choice of speed is not so critical as for other conditions. Point (6) on the inverted stall curve is seldom reached in practice and is not generally critical.

The application of the Flight Envelope to the aeroplane as a whole and for the full c.g. range ensures that rational tail loads result from the manoeuvres specified, provided that adequate data concerning elevator control displacements in relation to the manoeuvres specified is available, particularly at high Mach numbers. Originally empirical formulae for pitching accelerations

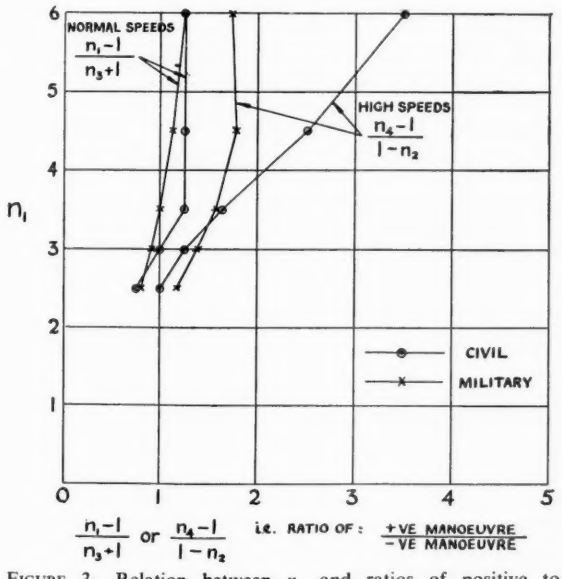


FIGURE 3. Relation between n_1 and ratios of positive to negative manoeuvring accelerations.

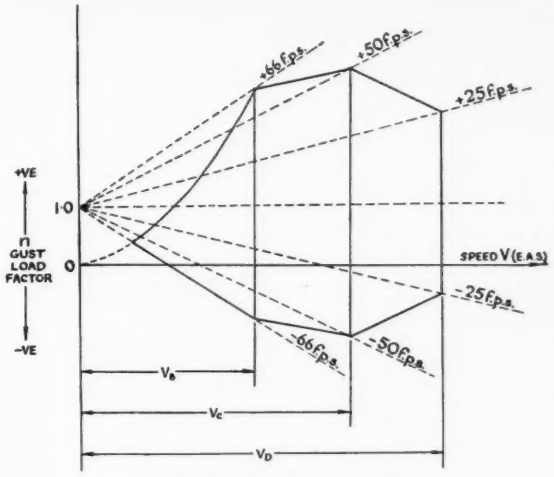


FIGURE 4. Basic gust envelope.

were derived from past experience with straight wings, but the advent of swept wings, higher Mach numbers and other modern trends, has made these formulae more inaccurate and the full manoeuvre calculations are now strongly advocated and desirable.

Elastic deflections of the structure must also be accounted for, since these can change aerodynamic loadings.

2.2. GUST CASES

Vertical gusts produce a change of aerofoil incidence, and the resulting additional loads are proportional to the product of gust speed and flight speed. Thus a series of straight lines radiating from the point $n=1$, $V=0$, on the flight envelope would represent gusts of varying intensity. At high Mach numbers compressibility effects cause these lines to be slightly curved. Fig. 4 shows the gust envelope for the three gusts specified in the civil requirements, associated with their respective design speeds. These are: —

(*i*) Gust Velocity = 66 f.p.s. at speed V_B
(*ii*) " " = 50 f.p.s. at speed V_C
(*iii*) " " = 25 f.p.s. at speed V_D.

(*i*) is the maximum gust intensity expected to be met, based on gust records taken in flight, and the associated design speed is the lowest speed at which the aircraft can fly in such conditions, and not stall.

(*ii*) and (*iii*) are reasonable combinations of lower gust speeds and higher aeroplane speeds based on the philosophy that if the aeroplane has met the worst gust, it is moving out of the centre of turbulence and therefore, although the speed of the aeroplane may inadvertently increase, the speed of the gust will almost certainly decrease. On the other hand, if the aeroplane is already flying at, or near, V_D in relatively calm air, the onset of turbulence will be indicated by low speed gusts initially, and the pilot can forthwith reduce his speed to suit the prevailing conditions. Adequate weather reports supplement such a philosophy.

A supporting argument is that the probability of occurrence of a high speed gust at a high aircraft speed is not great, since the aircraft seldom flies at its maximum speed. Hence, the combination (*iii*) and then (*i*) and (*ii*) follow logically. The military requirements are somewhat similar except that, at the moment, the specified aeroplane speeds are slightly less and the 66 f.p.s. gust is not specifically included. Some revision is under consideration, based on more recent flight data, which will line up these requirements in regard to speeds. Similar horizontal gust cases are considered.

The effect of altitude is allowed for on the basis of our limited knowledge at the present time, in both the civil and military fields; the present philosophy being that gust intensities and frequencies are generally less at altitude, but Mach number effects may tend to balance out these reductions. More research is needed above 30,000 ft. to extend the useful work done recently by British Overseas Airways, British European Airways and the Ministry of Supply.

In applying the foregoing, the gust gradient is of considerable importance, and in the absence of more accurate data it is assumed that the full gust velocity builds up linearly in a distance of 100 ft. and that this can be converted to an equivalent sharp-edged gust by applying a correcting or alleviating factor. The present requirements base this alleviating factor on wing loading, which basis is now known to be only part of the story. It is now believed to include the influence of: —

the mass of the aeroplane,
the aerofoil characteristics,
the wing chord in relation to the actual gust gradient distance,
the aspect ratio, and
the sweepback.

Revised requirements are under consideration.

While preliminary design can advantageously be made on a basis of equivalent sharp-edged gusts, it is becoming increasingly important on large modern aircraft to make a full dynamic response calculation as a final check, using more than one gust gradient, and the elastic characteristics of the wing structure.

2.3. ASYMMETRIC MANOEUVRES

(*i*) *Rolling*

Here, another version of flight envelope is envisaged in which the aeroplane is in symmetric flight at accelerations up to one half of the normal maximum positive acceleration (with an over-riding minimum value) and is then subject to a rolling manoeuvre, described by a specified minimum rate of roll (associated with a given speed and altitude). Since aerodynamic data on such matters, particularly at high values of M, is not always as accurate as is desirable, an additional factor of 1·33 is put on this rolling moment. A supplementary condition has also to be included, namely that control forces of 60 lb. for stick and 100 lb. for wheel control shall be satisfied. Should these produce greater rates of roll than the preceding, then these must be taken. Alternatively, the maximum output of power controls is used, in which case it appears desirable to apply an additional tolerance factor of safety of 1·2 to cover variation of power unit output.

In spite of these safeguards it has been found that high-speed aerobatic aircraft can be manoeuvred fairly easily to produce higher accelerations and, where appropriate, these must be included. On the other hand, for the large transport aeroplane, an unnecessarily large angle of bank may be reached before the steady rate of roll has been achieved. An arbitrary limiting angle of bank is then justified, compatible with operational requirements, and the manoeuvre then checked.

(*ii*) *Yawing*

As in the previous case of rolling, the yawing requirements are couched in general terms and recommended detail requirements are given for use where insufficient data is available from which to do full response calculations.

Although the present civil requirements specify an initial speed of V_A only, it is known that they are under revision and will cater for a full range of speeds, with appropriate rudder operation and rudder pedal forces. The civil requirements specify a checked manoeuvre, namely application of full rudder, except as limited by control effort, beginning with zero yaw, proceeding to an over-swing beyond the equilibrium angle of yaw, and returning *via* zero rudder angle to some fraction of equilibrium angle of yaw.

The more stringent operating conditions of military aircraft consider first a similar manoeuvre except for the return to zero rudder angle, and, in addition call for a sinusoidal rudder movement of $1\frac{1}{2}$ complete cycles, or 1 cycle only for transports, although with less rudder control force than the preceding case. The justification claimed for this is the evasive action necessary in time of war, which is of course true to some extent. Never the less, in practice this sometimes results in quite severe loads relative to the civil counterpart.

2.4. FLIGHT UNDER AUTOMATIC PILOT

In the interests of safety the auto-pilot must be designed so that its installation satisfies three things: —

(*i*) When engaged, it should not cause loads upon the aeroplane which are greater than the other design loads over the full range of speeds for which it is required, and for all altitudes and for the full c.g. range.

(*ii*) It can be engaged and disengaged by the human pilot readily and easily.

(*iii*) Automatic dis-engagement or mal-functioning must not produce excessive loads during the period between dis-engagement or mal-functioning and take-over by the human pilot. Provision for as long a period as possible, up to, say, 5 seconds, is desirable to guard against over-stressing the structure.

These conditions pose a number of design problems, the solution of some of which are debatable. But it must always be remembered that the auto-pilot must both operate safely and fail safely.

2.5. CONTROL SURFACE LOADS

In such a brief review as this, little more can be said beyond what is mentioned in the foregoing, except perhaps to call attention to the need to consider the effect of gusts on landing flaps, and the necessity for considering flap loads at moderate angles combined with approach speeds which are somewhat greater than take-off and landing speeds. Another important point here is the consideration of times of operation of such devices. They must be short enough not to prejudice the aeroplane performance and yet not so short as to lead to undue expenditure of weight on the operating mechanism.

2.6. ENGINE AND PROPELLER LOADS

Speaking very broadly, these only affect the strength of the local structure on which the power plant is mounted and, while these considerations are extremely important, they do not generally affect the aircraft as a whole. Engine Power, of course, does, and is included in the consideration of design speeds.

2.7. CABIN PRESSURE LOADS

These legitimately come within the scope of flight loads. The essential requirements are: —

(*i*) That since they are sustained loads, they must not produce stresses which exceed the elastic limit for the structural material used, or creep may result.

(*ii*) That since they occur frequently, fatigue life is of primary importance and to this end the stresses must again be kept low, stress concentrations must be avoided and special attention must be paid to stress gradients.

3. Future Trends

3.1. FLIGHT AT INCREASING SPEEDS AND ACCELERATIONS

The most important effect of these changes is that due to kinetic heating, which in turn arises from adiabatic compression of the air and from skin friction. This leads to high temperature gradients within the structure, and hence internal stresses, in addition to those from normal flight manoeuvres. Legislation will be required to control excessive temperature gradients, not only in terms of speed restrictions, but also in terms of forward acceleration restrictions, because high accelerations lead to higher, short-time temperature gradients. Limitations of time spent at a given speed may also have to be imposed because of the creep characteristics of even the more modern materials now envisaged, *e.g.* buckling of panels will be accelerated by creep and tension joints will develop back-lash from the same cause. Some degree of artificial cooling and of insulation may require to be specified, and it is suggested that at least the provision of accelerometers in the cockpit will be essential, if not the fitting of some form of *g* restrictor to operate within a limited range, together with some positive form of speed control.

3.2. FLIGHT AT HIGHER ALTITUDES

Already flight speed requirements are couched in terms of E.A.S. Speeds up to moderate altitudes and in terms of Mach numbers for higher altitudes, and the future outlook emphasises this need, since higher values of M for a given E.A.S. speed occur with increase of altitude.

Wing and control surface characteristics will require to be designed for optimum performance at these higher values of M. This may lead to different low speed characteristics, such as excessive buffeting, and requirements now governed by stalling speeds may well be governed in the future by the onset of buffeting or some other phenomenon.

High altitude gusts are still not fully appreciated and eventually gust requirements may have to be modified to account for these.

3.3. AERODYNAMIC DEVELOPMENTS

Boundary layer suction cannot be ignored as a possible influence on future requirements. At the moment no serious change is, however, imminent other than perhaps an increase in the slope of the lift curve, with consequent effect on gust loads.

The incorporation of jet flaps leads to a novel distribution of aerodynamic loading around the wing section, and provision for increased wing torques and overall wing twist may influence prescribed loading conditions. The disappearance of stall characteristics as we know them today, and changes in methods of control which will accompany the jet flap, will also call for new design criteria.

3.4. STRUCTURAL DEVELOPMENTS

Methods of estimating structural distortions on a modern wing are already in the process of revision because of the complex nature of the structure, and also because of new plan forms. Coupled with these changes, the aeroelastic requirements now specified for conventional wings will require to be restated, since they have little meaning when applied to, say, a delta wing.

Notwithstanding the use of new materials capable of resisting high temperatures for long periods, and exhibiting favourable temperature-strain characteristics we may be left with overall thermal distortions of wings, and tail surfaces. Similarly, increased aeroelastic changes may accompany wings designed for supersonic speeds. Both of these will have to be included in response calculations for manoeuvre loads.

3.5. FINAL COMMENT

Accident statistics in the past have shown that structural weaknesses account for well under 5 per cent. of the total, thereby indicating that design requirements for the safety of the structure have not been found seriously wanting. In the face of rapid developments we have to exert a keen vigilance in the future, in order to maintain, let alone improve, this comparatively good record.

ACKNOWLEDGMENTS

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Safety Factors

by

J. K. WILLIAMS, B.Sc., A.F.R.Ae.S.
(*Air Registration Board*)

1. Introduction

Three of the primary considerations involved in the design of an aeroplane are *safety*, *weight* and *serviceability*. The structure weight being a major item in the design which can influence its efficiency as a flying machine, the considerations of safety and serviceability have always to be studied with respect to their effect on the weight of the structure. The history of the development of aircraft structural design indicates clearly the tremendous amout of work which has been devoted to the development of higher strength materials and more accurate stressing and testing methods, always with the aim of ensuring adequate safety and reliability consistent with efficiency of design, construction, and operation.

2. Safety and Serviceability

2.1. STRUCTURAL FEATURES

The safety and serviceability features of the aeroplane structure are dependent upon:—

(*a*) *The properties of the structure* (*strength and aeroelastic*) initially as produced by the constructor, and subsequently as maintained in operation. The important factors contributing to the strength properties of the structure are:

Design conditions and additional margins or factors obtained from airworthiness standards (B.C.A.R. or A.P.970).

Methods of load analysis involving aerodynamic assumptions.

Methods of stress analysis.

Test methods to demonstrate the ability of the structure to withstand the assumed load distributions.

Properties of the materials of construction.

Consistency or otherwise of workmanship and workshop processes throughout the production line as compared with the initial test structures.

Maintenance of the original strength standard by the operator during the service life of the aeroplane.

(*b*) *The actual magnitude of loads and the corresponding frequency* with which they occur during the lifetime of the aeroplane.

Externally induced—atmospheric gusts and contact conditions with the ground.

Internally induced—pilot-induced loads dependent upon pilot behaviour and characteristics of the control system including auto-pilot.

—cabin pressure loads, hydraulic system loads, etc.

The operational technique used can influence the magnitude and frequency of these loads to a marked degree. For instance, the control of speed and altitude of operation by the pilot in turbulent air conditions may ensure that the maximum anticipated load, that is, the limit load, is not exceeded. Also the total utilisation of the aircraft in flying hours, which is an operational characteristic, directly affects the total frequency of all repeated loads.

2.2. LOADING CONDITIONS

The loading conditions for aircraft structures are thus of two distinct types with regard to their effect on the structure:—

(*i*) The loads of a high order of magnitude which occur very rarely during the lifetime of the aircraft which means that the probability of exceeding these loads is extremely remote. These loads are termed "*Limit Loads.*"

(*ii*) The loads which occur frequently. The low order of magnitude gusts may occur a few million times during the lifetime of the aircraft while the comparatively high order pressure cabin load, for example, is applied once per flight with a total number of applications between 10,000 and 20,000. These loads are termed "*Repeated Loads.*"

Associated with "Limit Loads" are two design factors:—

1. *Proof Factor* being the ratio of the design proof load to the design limit load. This factor is intended to ensure that up to, during, and after, the application of the limit load in operation the structure will still be in an airworthy condition; in other words, the structure will be serviceable

and free from detrimental deformation, cracks, pulled rivets, and so on. In addition, it is essential that moving parts, such as control systems, shall function satisfactorily under these conditions.

The British Civil Airworthiness Requirements (B.C.A.R.) specify a proof factor of 1·0 in conjunction with the limit load.

The British Military Requirements (A.P. 970) on the other hand, in general, specify a proof factor of $1\frac{1}{8}$. The reason for this difference in specified proof factors is probably the fact that in civil operation due to the controlled nature of the flying of the aircraft, the limit load is not often exceeded, while in military operations by necessity the limit load is reached and may frequently be exceeded.

2. *Ultimate Factor or Factor of Safety* being the ratio of the design ultimate load to the design limit load. This factor is intended to ensure that the probability of failure of the structure under the application of the limit load or loads exceeding the limit load shall be remote during the lifetime of the aircraft, having regard to the possible variation in the strength properties of the structure. In the civil requirements and, in general, the military requirements, this ultimate factor is 1·5 in conjunction with the limit loads.

Associated with the "Repeated Loads" is a fatigue factor of safety which takes account of variations of the load spectrum and of the scatter of the fatigue strength of a particular structural component.

3. Airworthiness Standards (B.C.A.R., A.P. 970)

For the design of an aeroplane type to a certain specification in this country, design firms will use a common set of standards—the British Civil Airworthiness Requirements for a civil type, and A.P. 970 for a military type. By employing such a common set of design standards incorporating identical safety factors in design, it must be assumed either that,

(*a*) All aircraft firms have the same basic engineering experience in the design and construction of the aircraft.

or,

(*b*) That the safety factors are intended in part to cover any significant differences in the design and construction capabilities of aircraft firms.

Likewise, when a common set of standards are agreed internationally at the International Civil Aviation Organisation (I.C.A.O.) meetings, the same arguments apply as between one firm in the United Kingdom and another firm in the United States, or other country such as France or Italy. Similar arguments apply to the operation of aircraft.

Thus, it is impossible to consider safety factors and other safety considerations as laid down in handbooks of Airworthiness Standards, civil or military, in the abstract and divorced from the vast background of the organisation of aviation in general throughout the world.

4. Types of Structural Failure

Significant ways in which an aeroplane structure can fail in operation are the following:

(*i*) *By flutter of wing or tail structure*

The onset of flutter being directly dependent on the aeroelastic properties of the structure, the safety factor used is expressed in terms of a *speed* margin. By resonance tests and flutter calculations it shall be demonstrated that the structure is free from flutter up to a speed 25 per cent. above the maximum placard diving speed of the aeroplane.

(*ii*) *By excessive yielding and distortion*

By the application of a single load above the onset of yielding but below the ultimate failure load of the structure, the aeroplane can suffer disaster by jamming of control runs, by loss of stability and control due to severe permanent distortion of the aerofoil surfaces, or by breaking electrical leads or fuel pipe lines.

(*iii*) *By ultimate failure* under the single application of a high load.

(*iv*) *By fatigue failure* of the structure under the repeated application of critical loads.

5. Past Experience

5.1. DEVELOPMENT OF MATERIALS

In the early period of development of aviation an acceptable safety level was achieved by the process of trial and error. The principal material of construction was *wood* and when these aeroplanes broke up in flight, the load factor was increased. Only the ultimate load factor was considered for design purposes and load tests on wings to ultimate destruction were characterised by a dramatic and sudden collapse.

In the early 1930's, *Aluminium Alloy* began to replace wood as the principal material of construction of aeroplanes designed to the same ultimate load factors as the old wooden types. The characteristic yielding properties of aluminium alloys, as demonstrated on static tests, resulted in the Airworthiness Authorities introducing the concept of a *proof factor* to prevent distortion and permanent set under flight conditions. The proof factor was required to be at least $\frac{5}{8}$ of the specified ultimate factor and the requirement was satisfied by using materials having 0·1 per cent. proof stresses not less than $\frac{5}{8}$ of their corresponding ultimate stresses.

Figure 1 illustrates how, since those early days, the ratio of (ultimate/proof) strength of aluminium alloys used in aircraft construction has decreased from 1·6 to 1·1 as the ultimate tensile strength has increased.

The proof factor, as such, has lost its original significance except for detail design, such as riveted joints.

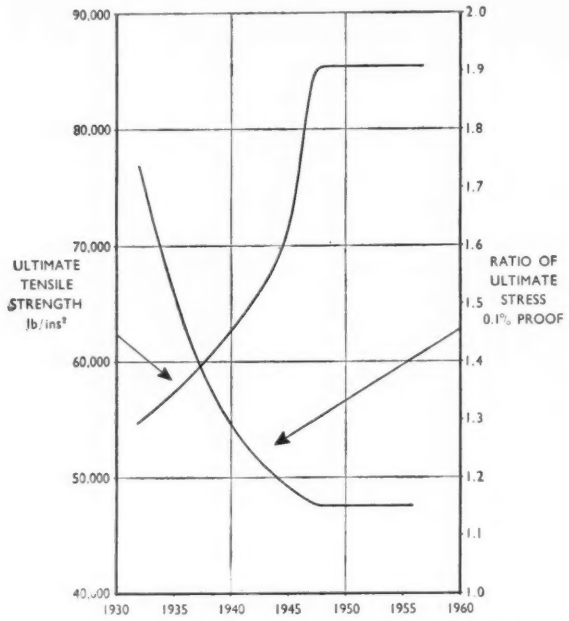


FIGURE 1. Trends in material properties of aluminium alloys.

Figure 2 illustrates the other fundamental change which has taken place in the properties of aluminium alloys, in that there has occurred a marked decrease in the fatigue strength with increasing ultimate strength. It is now established that on an alternating net stress basis there is no appreciable difference in fatigue strength, expressed in terms of load cycles to failure for aluminium alloys of the lower to the higher strength grades.

On this assumption, the curve of decreasing fatigue strength with increasing ultimate static strength has been established. It is also known that if the structural design strength of the wings of a Normal Category civil aircraft is based on the 50 f.p.s. gust case (B.C.A.R.) then the most critical gust magnitudes from a fatigue damage consideration are of the order of 10 f.p.s. corresponding to about 8 per cent. of the ultimate design case. This curve has been drawn from published data on fatigue test results for typical aircraft structural joints incorporating the normal order of design stress concentration.

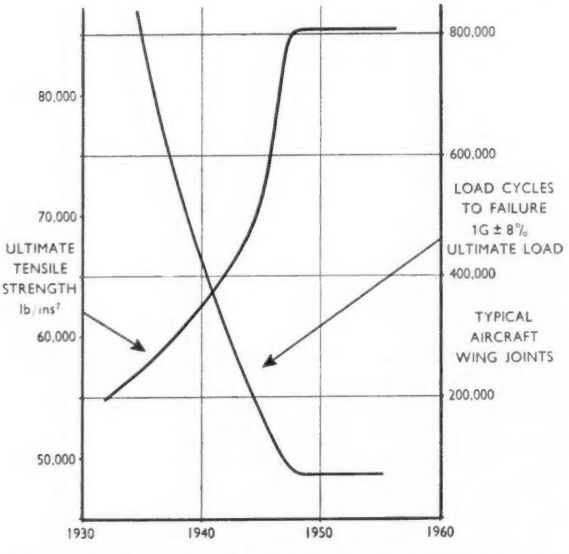


FIGURE 2. Trend in the fatigue strength properties of aluminium alloys.

Thus, from considerations of material properties alone, the identical aircraft flying under identical operational conditions would suffer an eightfold decrease in potential fatigue life if constructed to the same ultimate strengths in the early alloys and then from the contemporary high grade alloys.

There are, of course, other factors to consider when assessing the total fatigue hazard at any one period of time, such as the operational role of the aeroplane, involving climb and descent speeds, altitudes of operation and total utilisation.

5.2. DEVELOPMENT OF STRESSING TECHNIQUES

As the years progress there is greater concentration on stressing techniques and development of structural arrangements with the aim of producing a structure with more uniform efficiency. These techniques include the assessment of design loads, manoeuvring, gusts, and so on by aerodynamic assumptions of load distribution. Then by past experience of component testing, allowable stress assumptions are obtained to reduce structure weight to a minimum. This has resulted in the elimination of reserve margins of safety in the structure.

5.3. STRENGTH TESTS

Even though stressing techniques have become more exact, when ultimate strength tests are made some structures still fail well below the anticipated ultimate strength. As such, strength tests to destruction must still be regarded as the basis for the acceptance of a structure. Many arguments have been advanced for the elimination of the ultimate strength test, especially for military aircraft, mainly on the basis that the proof condition represents a realistic flight condition, but that at a certain stage between the proof and ultimate conditions, as was usually the case with past designs about 85 per cent. of the ultimate condition, the structure distorts to such an extent that the test after that stage cannot possibly represent any realistic flight condition even after the load is removed.

The main advantage of the ultimate strength test is that the final breaking load can be conveniently demonstrated, whereas it is extremely difficult on a full-scale test to demonstrate the airworthiness of a structure at proof load. Undoubtedly the ultimate strength test in the past has demonstrated the ability of the structure to withstand a load between the proof and ultimate loads, and if this occurred in flight, the aeroplane returned to the 1*g* condition retaining an adequate measure of strength, stability and control to return to base. A great deal of local damage might have resulted

in pulled rivets and permanent set of certain components, and so on. This has occurred frequently in conditions of severe turbulence.

5.4. GUST LOADING CONDITIONS

Figure 3 illustrates the conventional flight envelope for gust design which represents the limit gust design condition with which is associated a proof factor of 1·0 in civil requirements. This envelope represents a boundary of extreme conditions achieved during the lifetime of the aeroplane. It crystallises the results of a considerable amount of experience gained in the operation of piston-engined aircraft during the past 20 years. It illustrates the fact that the achievement of a level of safety from structural considerations has depended fundamentally on the use of an operational technique by the pilot, based on his experience, weather information, and knowledge of recommended safe speeds corresponding to the structural limitations of the aircraft. The greater portion of the operating time is spent below V_{NO} the normal operating speed and the corresponding altitude. However, a lower rough air speed is recommended for flying in turbulent conditions and this is a speed above that at which the aeroplane will stall under the action of the highest anticipated gust (66 f.p.s.) but is lower than the speed which will cause structural damage under the action of the same intensity gust.

This 66 f.p.s. gust is not the highest intensity gust experienced in the atmosphere, but from past experience it has proved to be of sufficient magnitude to ensure an adequate safety level for the piston-engined aircraft types.

An extremely important contribution to safety was the study of the magnitude of gusts experienced in thunderstorms, and the behaviour of aeroplanes when flying through heavy turbulence, obtained by the United States Thunderstorm Project in 1947. The results of this research indicated that the maximum gust intensity encountered was 72 f.p.s. Also important from the safety aspect was the conclusion that pilot technique influenced the accleration measurements so that the final "gust load" was a combination of the actual gust effect and pilot augmentation.

Accelerometer records on civil aircraft operated on particular routes in the United States show that the limit gust load was exceeded about twice in one million flying miles (one up, one down) at altitudes up to 10,000 feet, *i.e.* once in about 2,500 flying hours for the piston-engined type aircraft. This frequency is a relatively high one, about once a year for every aeroplane flying at this utilisation rate.

Figure 4 indicates how, for one type of four-engined U.S. civil transport, the limit design gust strength envelope has been exceeded during about 50,000 recorded hours of flying up to 10,000 feet. The U.S.A. and U.K. civil gust requirements are identical in these respects. Theoretically then, many aeroplanes in the past have been flying in the region of permanent set, but the unserviceability rate for civil aircraft during the past 10 years because of this has not been unduly high, because the actual properties of the wing structures have been such that the actual proof conditions have been well above the limit load conditions.

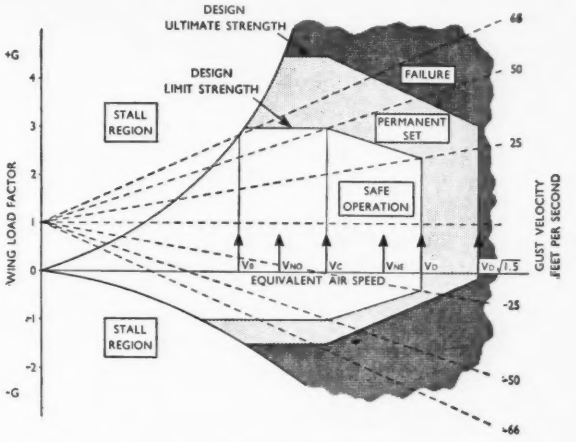


FIGURE 3. Typical gust-strength envelope for civil aircraft.

These gust standards were developed and introduced 10 years ago, based on the American experience and records up to that date. A vast amount of gust research work has been carried out during the past ten years, both on the high gust values and on the lower order gusts from fatigue considerations at all altitudes up to 40,000 ft. Thus, the next stage has been reached for a further review of the gust standards, both for low and high altitude operations.

6. Design Criteria—Static and Fatigue

Figure 5 illustrates the safety factor concepts for the static and fatigue conditions. Both concepts cover:

Variations in structural strength
Variations in load pattern.

In stipulating a set of generalised design conditions,

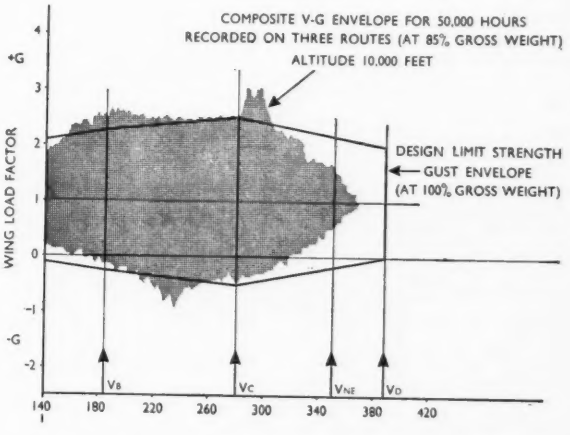


FIGURE 4. Comparison between design limit strength gust envelope and actual *V-g* data for U.S. four-engined transport (N.A.C.A. T.N. 3051).

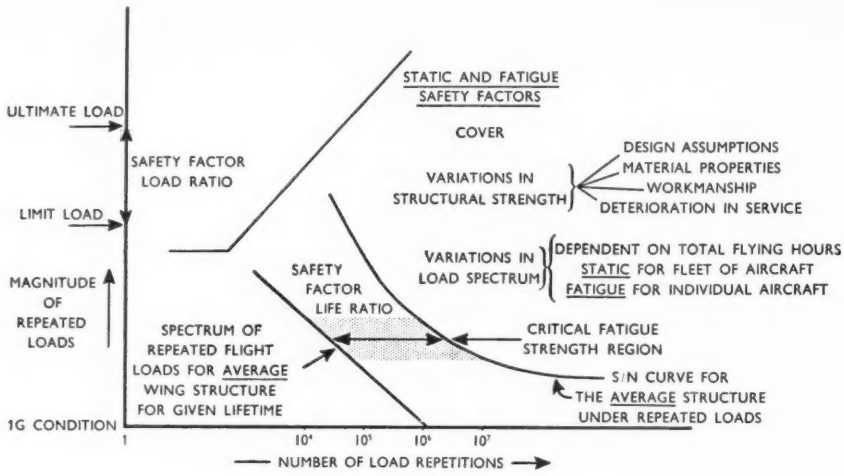


FIGURE 5. Illustration of safety factor concepts for wing design of civil aircraft (1955).

such as a gust envelope for different types of aircraft of differing all-up weights and types of construction, to be designed by different design teams, it is inevitable that the assumptions made by these design teams in translating the effects of gusts and other loads on to their respective structures will differ to some degree. This is especially so when Mach number effects are involved. For example, two aircraft designed by different design teams to the same specification, the wings from each aeroplane being tested to the loads calculated by the respective design teams, may differ in actual strength resistance to the same gusts, even though each wing on test may fail exactly at 100 per cent. ultimate load.

Even though a specialised degree of quality control is exercised in all the processes of construction of aircraft, the variations of material properties in workmanship, workshop processes, and deterioration in service by corrosion, wear, repair and general maintenance, must contribute appreciably to variations in structural strength between the best constructed aircraft of a fleet at the beginning of its service life and the worst constructed aircraft after 5 years or so in operation.

The variation in load pattern is dependent on time of exposure, *i.e.* total flying hours. The *ultimate safety factor* caters for the probability of one or more aircraft in a fleet of aircraft exceeding the design limit load in a specified period of flying hours. In this case it is the *total* flying hours of the fleet which matters irrespective of whether there is a large number of aircraft flying for a short period or a small number of aircraft flying for a long period. Thus, the variation in load pattern in this case is expressed in terms of a *load factor* when the effect of a variation in a load pattern is considered for one aircraft in the fleet in combination with variations of structural strength.

The *fatigue safety factor* caters for the progressive repetition of loads for each individual aircraft irrespective of what happens to the other aircraft in the fleet. Thus the variation in load pattern in this case is expressed in terms of a *life factor* when combined with variations of structural strength.

The magnitude of the fatigue life safety factor used when specifying retirement lives for structural components on British Civil Aircraft is of the order of *6·0* as applied to the calculated life of an average structural component operated in average load conditions. This factor is necessarily conservative during the present interim stage before aircraft specifically designed for an adequate fatigue life are brought into operation. If instead of designing a structure such as a one- or two-spar configuration at such low working stresses to ensure an adequate fatigue life, a structure is designed specifically with "fail safe" considerations in view, then the claimed safety qualities of such a design should be substantiated by calculation and by appropriate tests.

Figure 6 illustrates an example of what is claimed to be a typical "fail safe" wing structure, each of the lower spar booms carrying about 20 per cent. for the tension load, the remaining load being carried by the stringers and skin. The safety factors or considerations to be applied to such a structure should ensure that, during the period from the initiation of a fatigue crack to the time when the crack is of such a length as to be readily detected by inspection, the structure should retain a certain strength standard.

For example, consider what can happen to this type of structure if a fatigue crack develops in the centre spar lower boom. At some stage in the progression of the crack this boom will fracture suddenly while the whole wing is under load, and the load carried by this centre boom will be redistributed dynamically to the surrounding structure. This may occur under turbulent conditions, and after boom fracture the aircraft may have to fly on for some time.

Thus two basic structure test cases arise for the airworthiness approval of such structures—

(*i*) Demonstration that the wing can withstand the sudden failure of a major component while under load (half the limit load is suggested).

(*ii*) Demonstration that after the failure of a major component the wing can withstand a certain load (1·2 times the limit load is suggested).

Similar considerations should be given to the pressure cabins and other structural components.

7. Achieved Level of Safety

The degree of safety from structural considerations in civil aviation has been achieved by experience on a step-by-step process, often after severe set backs. This degree of safety must always have been related to the *ultimate strength* criterion (positive and negative) as demonstrated by ultimate tests to destruction. The fact that measurements of limit loads in practice indicate that the ratio of 1·5 for the (ultimate/limit) load is of the right order, is a tribute to the intuition of the people concerned in drafting such standards in the beginning. The degree of safety achieved in this way has not been too low otherwise the accident rate would be unacceptably high. On the other hand, it is not too high because accidents, due to structural break-ups, have occurred at intervals during the past ten years on British civil aircraft.

Of the civil aircraft from 8,000 lb. up to 100,000 lb. all-up weight, comprising eight different types of British design, operating all over the world, there have been 16 accidents due to structural causes since 1948:—

Seven—fatigue 2 wing spar booms
2 pressure cabins
3 spar webs to boom attachments
six—break-ups in turbulence
three—on test flights

Some of these structural break-ups were primary wing-down load failures, indicating failure of the wing in a dive when the aeroplane has developed excessive speed probably associated with temporary loss of control in turbulence. The remaining break-ups, due to wing-up load failure, probably resulted from pilot action in recovery from a dive condition. Another important result following from the accident investigations is that several of the wing-up load failures were associated with two aeroplane types, each having light elevator control characteristics—of the order of *30 lb.* stick force to proof (*g*) of the aeroplane. This order of stick force is low compared with the characteristics of most other aeroplanes—*80 lb.* stick force to proof (*g*).

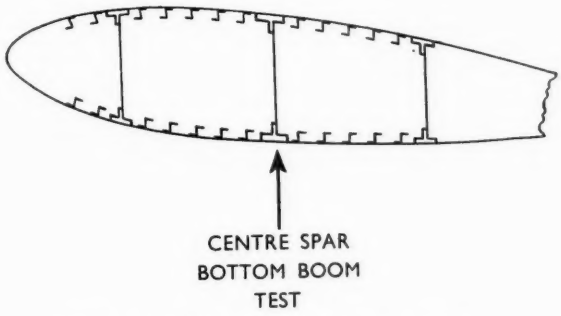


FIGURE 6. Typical "fail safe" wing structure.

Because the degree of safety must always have been related to the ultimate strength, then to appreciate the significance of the margin between limit and ultimate load it is necessary to start at the top level of ultimate load and work downwards towards the limit load, rather than start with the lower level of limit and then think of the 50 per cent. margin as something to be justified on top of the limit load.

On the assumption that the ultimate load specifications up to now have proved to be satisfactory, then the specification of a limit load with ultimate factor 1·5 or (1·25 × the same limit load) with an ultimate factor of 1·20 will achieve the same object from the safety aspect although from the serviceability aspect the latter is preferable.

Since the argument in this paper has been developed for the most important structural component in the aeroplane, *i.e.* the wing, which, as an aerofoil generating lift, is the whole basis of the aeroplane as a flying machine, it is only fair to mention that, for other parts of the structure where the effect of aerofoil characteristics do not enter, such as the fuselage under static loads and the undercarriage in which maximum load is specified by the characteristics of the shock absorber, then there is a case for a relative reduction in the ratio of (ultimate/limit) loads, as compared with the wing. Fuselage failures in structural break-ups are, in most cases, secondary to the wing.

8. Problems on New Aircraft Types

Accidents to aeroplanes due to structural failure apart from fatigue have always happened, and they are bound to occur in the future whatever precautions are taken beforehand, because it is impossible to achieve *absolute safety* from structural considerations, and in fact, it would be unwise to attempt to achieve this absolute standard because of the structural inefficiency it would entail.

However, an acceptable level of structural safety has been achieved in the past ten years for aeroplanes in civil operation, this level being linked to the ultimate strength criterion, and this criterion is then associated with a *technique* which involves the following:—

1. Common set of airworthiness load standards, defining limit and ultimate loads.
2. Aerodynamic load assumptions and methods of stressing, although varying to some degree between design teams, are in the main based on a common pool of knowledge.
3. The demonstration of a strength standard in the structure has been made by a test procedure to ultimate breaking load; the methods of testing are again in the main common to all aeroplanes, tests usually being carried out under the supervision of the R.A.E.
4. In any given year the materials of construction are common to most aeroplanes.
5. The aeroplanes concerned were all piston-

engined types with the following operational characteristics:—

(*i*) Maximum dive speeds not exceeding 350 knots I.A.S.

(*ii*) The normal operating speeds well below the design cruising speeds $V_{NO} \not> 0{\cdot}8\,V_C$.

(*iii*) Altitudes of operation mostly up to 10,000 ft. with the maximum 20,000 ft.

(*iv*) All-up weights not exceeding 120,000 lb.

(*v*) The controls for most aeroplanes showed reasonable stick force characteristics for elevator, rudder, and aileron controls and were not unduly light.

6. The wing configuration was what is now termed as conventional, in that there was little or no sweepback, aspect ratios about 10, moderately thick wings, with small amount of flexibility.

The level of safety achieved being associated with this combined technique, we are now faced with a new generation of aeroplanes which, compared with the older types, exhibit the following changed characteristics, as shown on Fig. 6. These aeroplanes will be turbine-powered with:—

(*i*) Maximum dive speeds up to a Mach number of 0·8 thus introducing non-linearity of aerodynamic coefficients with speed.

(*ii*) Normal operating speeds approaching the design cruising speeds, thus eliminating the hidden margin of strength in previous aeroplanes.

(*iii*) Altitudes of operation up to 40,000 feet.

(*iv*) All-up weights up to 200,000 lb.

(*v*) With the introduction of control assistance to the pilot some aeroplanes may incorporate unduly light control feel characteristics compared with the majority of the older types of aeroplane. This change could adversely affect the safety of the aeroplane in turbulence.

(*vi*) Thin wings, appreciable flexibility and sweepback.

(*vii*) Increased pressure cabin loads.

The resulting comparison results in the following main conclusions.

1. The fatigue design case assumes even greater importance to cover, not only wing structure, but also pressurised fuselages.

2. Due to the change in operating technique in that actual operating speeds, climb, cruise and descent are much nearer the actual structural design speed V_C than for the previous generation of aircraft, a greater responsibility now rests on the pilot to avoid structural damage or complete failure of the structure by control of speed and altitude when given warning of turbulent conditions. This responsibility the pilot should be able to carry out successfully, given a control system with characteristics not dissimilar to those on the previous generation of aircraft. An additional change involving a much lighter control feel system, associated with small

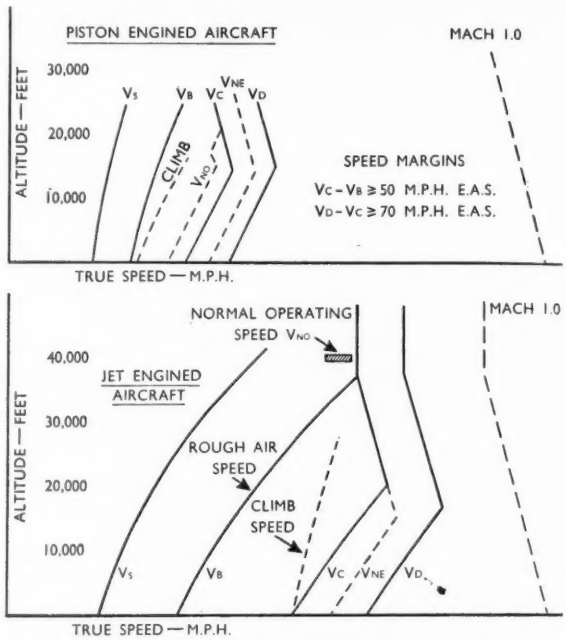


FIGURE 7. Comparison of operating techniques for piston and jet-engined aircraft.

movements to reach proof loads of the structure, may substantially affect the safety aspects of the structure.

3. Full account should be taken of the effects of increased wing flexibility and the Mach number effects on aerodynamic loading assumptions. These mainly affect the limit design case.

9. Conclusions

1. The approach to structural safety is based on experience, compromise and intuitive judgment.

2. There must always be an appreciation in good time of the significance of the strength properties of the structure when subjected to the anticipated critical range of loading conditions.

3. The structure must always be a reasonably sound one. This presupposes that adequate consideration has been given to detail design, inspection, workmanship and consistency of workshop processes which includes the manufacture of the basic materials of construction both during the initial design and construction stages and subsequently during its service lifetime.

4. Mathematical analysis of structural safety involving the statistical approach to probabilities of structural failure cannot be of much use while aircraft design and operating techniques are changing so rapidly.

Acknowledgment

For the history of the development of the concept of "Safety Factors," the author is especially indebted to the numerous papers on this subject written by Sir Alfred Pugsley.

Aircraft Fatigue

by

H. GIDDINGS, A.F.R.Ae.S.
(*Bristol Aircraft Ltd.*)

1. Introduction

As the treatment of the different subjects must be brief and general this paper can only deal with the complex subject of aircraft fatigue in very broad terms, attempting to trace the development of the subject over the past ten years or so, to present some of the problems and the methods being adopted to solve them and to emphasise the very wide extent to which fatigue affects aircraft design today.

The fatigue of metals was recognised as a separate form of failure as long ago as 1854 and is now the subject of a very extensive literature. Mechanical engineers have long been familiar with fatigue as a criterion of design and are apt to be critical and even amused at the aeronautical engineer's recently found interest. The aeroplane not only has the mechanical engineer's fatigue problems associated with machinery powered by the internal combustion engine, and from such common features as wheels and brakes, but also those resulting from the unsteady nature of the air in which it flies and the change from ground loading conditions to air loading conditions which occurs once every flight.

The widely varying nature of the fatigue loads met by an aircraft, compared with most machinery run at fairly constant conditions, is one reason for the relative difficulty of the aircraft problem. The other reason for this difficulty lies in the different fatigue properties of the materials used. Steel is almost universally used in mechanical engineering and, fortunately for mechanical engineers, has a fairly clearly defined limit of fatigue stress. Thus the mechanical fatigue problem resolves itself fairly simply to keeping the stress in the fatigue loading condition suitably below the allowable fatigue stress for the steel being used.

In contrast, and most unfortunately for the aeronautical engineer, the aluminium alloy materials used in aeroplanes show no such fatigue limit. As the fatigue stress is reduced the fatigue life increases but remains finite. This material property, when associated with the widely varying loading conditions, presents an extremely difficult problem in design and will be referred to again later. Fig. 8 gives examples of fatigue or *S-N* curves for steel and aluminium alloy materials and illustrates the typical difference in behaviour.

One of the earliest attempts to formulate a fatigue requirement for aircraft was by Professor (now Sir Alfred) Pugsley in 1942. He had in mind the effect of atmospheric turbulence on wings and tailplanes and put forward a test requirement that the structure should still be airworthy up to 20×10^6 cycles, and should not fail before 50×10^6 cycles of a fluctuating load of ± 10 per cent. about the steady level flight loading condition.

Aircraft designers at the time had many much more pressing problems than fatigue with the military aircraft with which they were then entirely occupied and not much work was done along these lines.

It is a point of striking interest, however, that Sweden, not being directly involved in the 1939-45 War, chose to make a particularly close study of the fatigue problem. A detailed review of the subject was made in a paper by Bo Lundberg in 1947 and this was presented at the Second Session of the Provisional International Civil Aviation Organisation. This work again primarily considered the effect of atmospheric turbulence on wings but is a very complete and accurate forecast of the fatigue position today. Lundberg examined, in some detail, the three main elements in the fatigue problem:

(*a*) The collection of data on the frequency of occurrence of fatigue loads.

(*b*) Fatigue tests on the structural elements to obtain fatigue strength data.

(*c*) The correlation of (*a*) and (*b*) by damage theory to predict operational life.

Figure 1 is taken from this report and illustrates the then estimated range of the relationship between design ultimate factor and fatigue life. Obviously there were grounds for concern which have, unfortunately, since proved to be well founded, but again insufficient notice was taken of the predictions.

It is also interesting that at this same time, 1947, George Snyder of the Boeing Aircraft Company, presented a paper drawing attention to the problem of pressure cabin fatigue. He drew attention to the inadequacy of the required static factor of 2·0 for

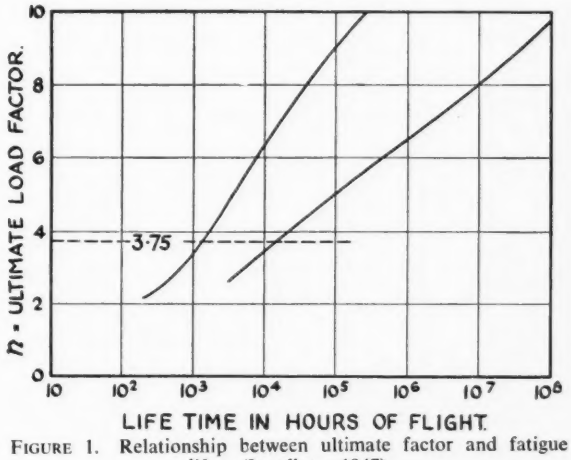


FIGURE 1. Relationship between ultimate factor and fatigue life. (Lundberg 1947).

covering fatigue strength and recommended a factor of 3·0 on structure designed by pressure alone.

In 1948 a fatal accident occured to a Martin 202 aircraft as the result of a fatigue failure of the wing spar joint. In 1951 a fatal accident occurred to a Dove aircraft due to a similar cause and at about the same time spar fatigue fractures were found on other Dove and Viking aircraft.

Since those events intensive work has been done on the wing fatigue problem, notably at the Royal Aircraft Establishment, and in Australia, and the cost to aircraft manufacturers and operators has been high. The fatal accidents to Comet aircraft in 1954 as the result of pressure cabin fatigue illustrates how slowly the earlier experience and work on wings has been extended to other components of the aircraft.

It is my own view, and the main theme of this short paper, that no primary component of the airframe can be excluded from fatigue considerations in design.

In assessing the difficulties of this task, however, it is perhaps useful to compare the basic fatigue problem with that of strength under static loads.

Figure 2 presents the static strength equation

$$\frac{\text{Limit load} \times \text{Factor of Safety}}{\text{Ultimate static strength}} = 1{\cdot}0$$

and the fatigue strength equation

$$\left(\frac{n_1}{N_1}\right)_{P_1} + \left(\frac{n_2}{N_2}\right)_{P_2} \cdots\cdots = \Sigma\left(\frac{n}{N}\right) = \frac{1{\cdot}0}{\text{Factor of Safety}}$$

where n_1, n_2, etc., are the number of times the load oscillations P_1, P_2, etc., occur during the specified life of the aircraft, and N_1, N_2, etc., are the number of times those loads have to be applied, separately, to produce failure.

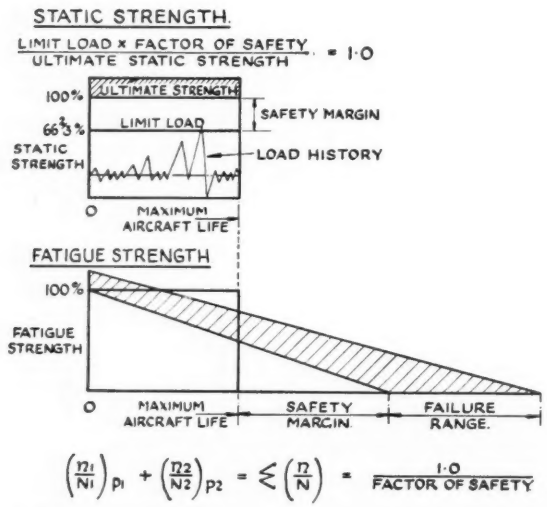

STATIC STRENGTH.
LIMIT LOAD x FACTOR OF SAFETY / ULTIMATE STATIC STRENGTH = 1·0
100%
ULTIMATE STRENGTH
SAFETY MARGIN
66⅔%
LIMIT LOAD
STATIC STRENGTH
LOAD HISTORY
O
MAXIMUM AIRCRAFT LIFE
FATIGUE STRENGTH
100%
FATIGUE STRENGTH
O
MAXIMUM AIRCRAFT LIFE
SAFETY MARGIN
FAILURE RANGE.
(n1/N1)P1 + (n2/N2)P2 = Σ(n/N) = 1·0 / FACTOR OF SAFETY
n1, n2, ETC. ARE NUMBER OF OSCILLATIONS OF LOAD RANGES P1, P2, ETC. DURING AIRCRAFT LIFE.
N1, N2, ETC. ARE NUMBER OF TIMES LOADS HAVE TO BE APPLIED SEPARATELY TO CAUSE FAILURE.

FIGURE 2. Comparison of static and fatigue strength requirements.

In the static equation the limit loads and factor of safety are well established and ultimate strength is obtained relatively easily and accurately by static tests.

In the fatigue equation, however, none of the terms is known accurately, nor can they be established easily or with the necessary accuracy. Thus the load oscillation magnitudes P_1, P_2, etc., are not easily determined, neither are the corresponding frequency terms n_1, n_2, etc. The fatigue life terms may be obtained by lengthy and expensive tests but the results are always associated with very wide scatter. Finally, it is extremely difficult to fix the Factor of Safety by rational considerations, partly because of this fatigue strength scatter, partly because of uncertainties regarding the loading terms and partly because of doubts regarding the validity of this basic "cumulative damage" equation itself.

Figure 2 also illustrates the difference between static and fatigue strength factors of safety, diagrammatically, against the life of the aircraft.

As a result of these and other difficulties many aircraft engineers believe that it is not possible to ensure, by design, testing and analysis, that fatigue failure of aircraft components will not occur during the life of an aircraft, with the necessary confidence, except at an unacceptable weight, and hence, economic, penalty.

This belief leads to a further consideration or requirement, that should a fatigue crack unfortunately occur in operation, then it must develop slowly and must not lead to an unacceptable loss of static strength before inspection and repair is possible. Briefly, the failure must be "safe."

This requirement has the additional merit that it guards against damage other than fatigue such as faulty ground maintenance, stones, ice, or secondary damage as the result of some other failure in flight not in itself catastrophic.

2. Fatigue Loading Conditions

It is sometimes not realised that each time an aircraft flies, one cycle of a significant fatigue loading condition is completed for many parts of the airframe.

Loads with frequency of approx. once per flight	*Loads with frequency of many times per flight*
1·0*g* wing lift	Wing loads due to gusts and manoeuvres
Tail balance load	Tail loads due to gusts and manoeuvres
Flap loads	Fin loads due to gusts and manoeuvres
Pressure cabin loads	Fuselage loads due to gusts and manoeuvres
Undercarriage vertical load	Flap loads due to gusts and manoeuvres
Undercarriage drag load	Propeller, slip stream or jet stream vibrations
Undercarriage side load	Engine order vibrations
Undercarriage retraction loads	Hydraulic pressure loads
	Undercarriage oscillations due to drag or runway roughness
	Undercarriage brake loads
	Undercarriage steering loads
	Flying control loads

FIGURE 3. Aircraft fatigue loads.

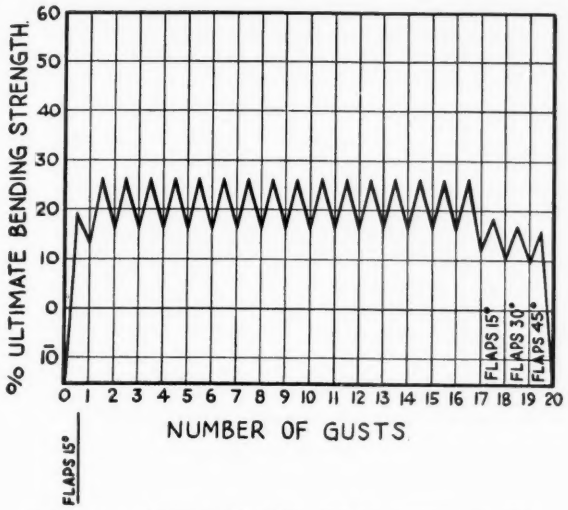


FIGURE 4. Britannia 100 wing bending moment at root.

A modern civil air liner is expected to carry out some 30,000-40,000 hours flying in perhaps 10 years, *i.e.* 10,000 flights if a 3-4 hour average flight is assumed.

Figure 3 tabulates the various aircraft fatigue loads into two groups, those with a frequency of once per flight (total number of cycles approx. 10^4) and those with a frequency of many times per flight (total number of cycles between 10^4 and 10^8).

An example of a particular fatigue load history is given in Fig. 4. This shows the variation in wing bending moment on the Britannia during a typical flight, the flight time scale being in terms of the equivalent number of 10 ft./sec. gusts, *i.e.* 20 such gusts per flight of $4\frac{1}{3}$ hours. There are three fatigue loading components in this case, the change from ground to level flight and back to ground, the raising and incremental lowering of the flaps, and the gusts. It should be noted that the incremental lowering of the flaps in itself introduces additional load cycles. The importance of fatigue loads due to flaps is even more apparent when one considers rear spar shears and this is shown in Fig. 5.

The effect of the gusts is quite small but that of flap loads plus those of level flight is significantly large.

Figure 6 shows the changes in tailplane load due to gusts and flap operation. The balance tail load is, in this case, negligible. The effect of the incremental flap lowering is roughly to add the equivalent of another two gust loadings to the 20 actual gusts, these two being at a higher mean load.

Figure 7 shows the "flight plan" which has been simulated in the Britannia tank fatigue test. It will be seen that the cabin is pressurised for 7 of the total of 20 equivalent 10 ft./sec. gusts and that 13 of these gusts occur during climb and descent conditions. It follows, therefore, that most of the fatigue damage due to gusts is done during climb and descent and that careful choice of these conditions in operation can significantly increase the aircraft fatigue life.

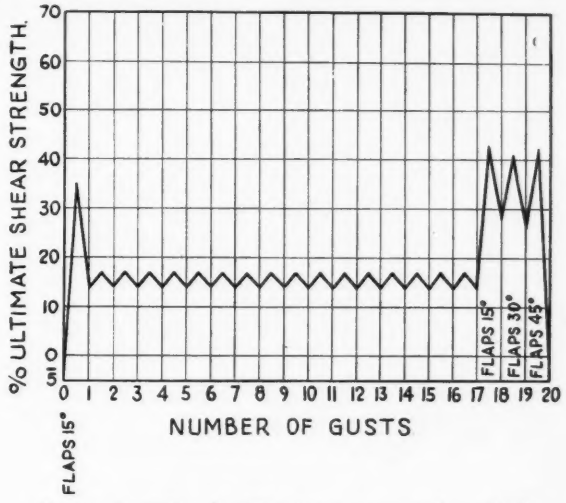


FIGURE 5. Britannia 100 wing rear spar shear loads.

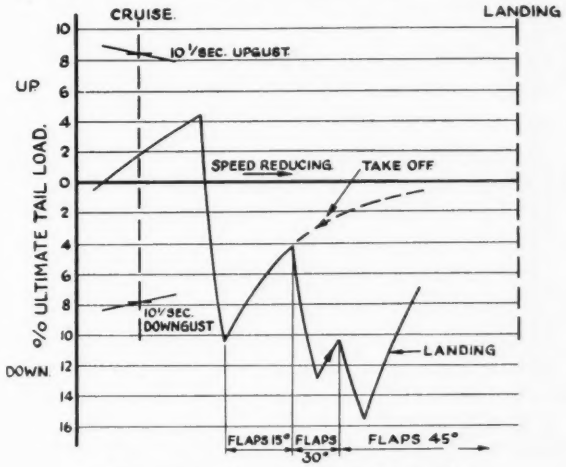


FIGURE 6. Britannia 100 tailplane loads.

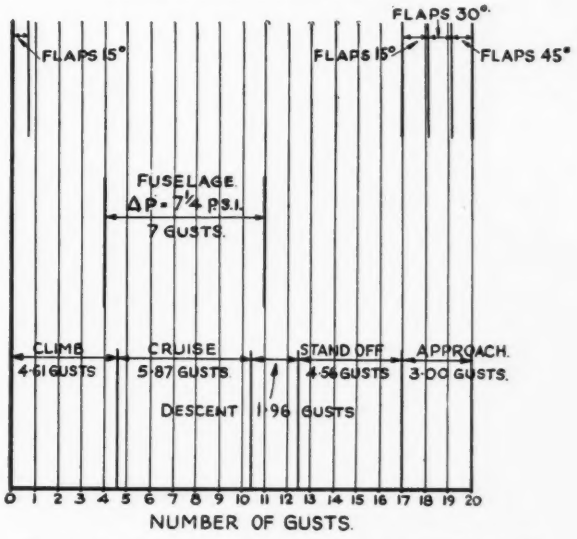


FIGURE 7. Britannia 100 tank fatigue test "flight plan."

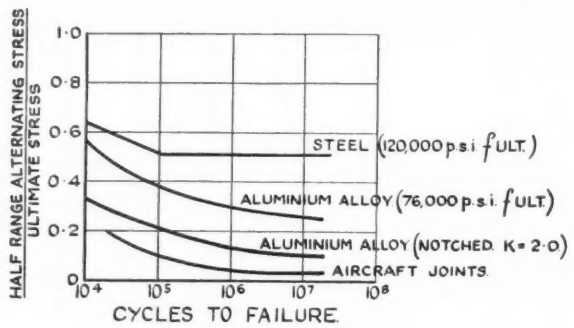


FIGURE 8. Typical *S-N* curves.

Other loads worthy of mention are those on the undercarriage. The trend of civil aircraft is to provide softer undercarriages so as to improve passenger comfort. If the undercarriage and associated structure are designed down to the reduced static factors associated with this softness, then fatigue life will almost certainly be inadequate. Stated the other way, fatigue requirements will over-ride static requirements in the design. The maximum undercarriage reaction factor (λ) on the Britannia is 1·85 and the specified static factor of safety is 1·5. If the undercarriage were designed solely to these criteria then loads of approximately 40 per cent. of static ultimate would occur once every landing, *i.e.* approximately 10^4 cycles.

Another special fatigue case arises with jacks and other hydraulic components, including those used to operate the undercarriage. The factor of safety required for static strength is 2·0 on the hydraulic working pressure. Again, if this is accepted as the sole design criterion, then loads approximately 50 per cent. of ultimate will occur at least 10^4 cycles during the life of the aircraft.

In both of these cases loads of lower magnitudes but higher frequencies, due to ground manoeuvres and runway roughness in the undercarriage case, and to pressure fluctuations in the case of hydraulic components, will be superimposed upon the above loads and will add to the fatigue damage.

Fatigue loads can, in general, only be approximated by calculation, but such approximations can form a valuable guide in design.

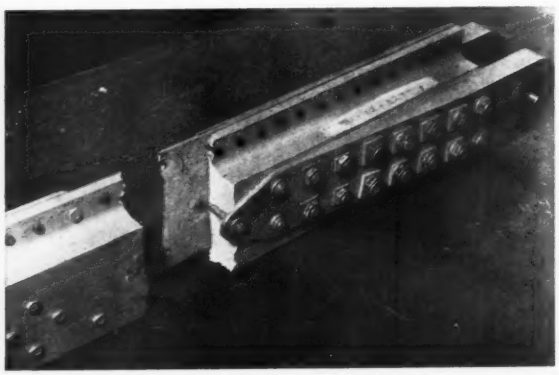


FIGURE 9. Bristol Freighter wing spar joint.

In addition to calculations some considerable part of the flight development time on a prototype aircraft has to be spent in measuring such loads. Continuous recording strain gauge equipment, counting accelerometers and counting strain gauges are all used in this work. The present counting strain gauges are mechanical and operate on too large a gauge length. A counting unit for use with standard electrical strain gauges would be a great advantage.

The routine use of counting accelerometers and strain counters by operators is also very necessary, not only as a source of statistical data, but as a means to enable control of flight plans so that fatigue damage is minimised.

Most fatigue loading conditions, as distinct from fatigue stresses, are fundamental and the designer can do little or nothing about them. In some cases, however, the operator can reduce these loads.

Before leaving the subject of loads, I would like to mention the problem of internal stress. This can arise from incorrect fit in a fabricated assembly, or in forging or heat treatment, and can quite easily amount to 10,000 p.s.i. in aluminium alloy parts. The effect, as far as fatigue is concerned, is equivalent to that of raising the mean load. This is a factor which the production engineer can do something about, by control of tolerances and fits, by the use of correct heat treatment temperatures and by the use of intermediate stress relief treatments in machining operations.

3. Fatigue Strength and Design

The strength of materials is an empirical science and this is particularly true of fatigue strength. The solid state physicists are still only skirmishing with tentative physical theories of fatigue and I think that, long term, the metallurgist will be able to do very little towards improving materials from this point of view until a sound physical theory is established.

There is a great deal of fatigue strength test data in existence but not easily available to the aeronautical engineer or easily applied to his problems. A Royal Aeronautical Society Handbook of Data Sheets on fatigue would be extremely useful in aircraft design offices.

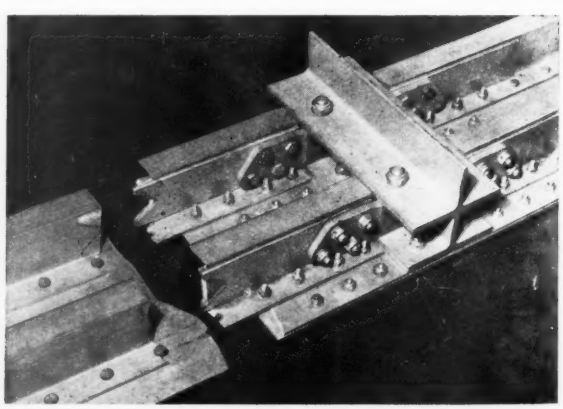


FIGURE 10. Britannia wing skin-stringer joint at the centre line of the aircraft.

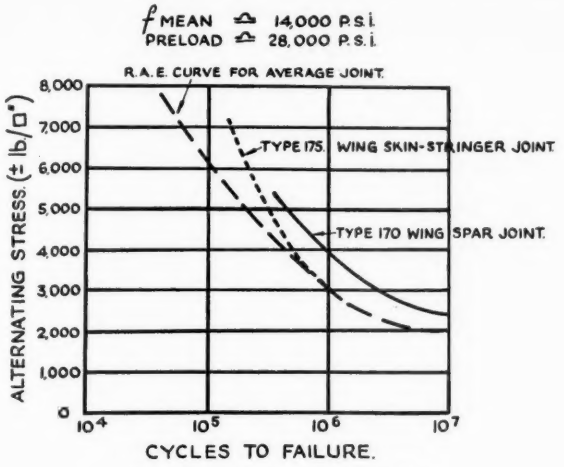


FIGURE 11. *S-N* curves for wing joints.

Figure 8 shows some typical fatigue *S-N* curves. The clearly defined " endurance stress " for the steel is apparent. Also to be noted is the effect of the notch in reducing the fatigue strength of the aluminium alloy and the further reduction which is obtained in an actual fabricated joint. It is obvious that nothing like the full fatigue strength of the material is realised in the actual structure and this fact is a challenge to the designer.

The elimination or reduction of stress concentrations is the method for improvement and this can be applied in practice in better detail design, the use of metal adhesives and a wider use of integral machined structures. In static strength design it is customary to ignore local stress concentration factors and the ductility of the materials used allows this to be done. In fatigue design, however, the local elastic strains are important and theoretical stress concentration factors must be taken into account in assessing fatigue stresses.

Figure 9 shows the main wing spar boom joint on the Bristol Freighter aircraft, while Fig. 10 shows, in contrast, the joint for the wing skin-stringer structure of the Britannia. In the latter example " Reduxed " reinforcing plates are used on both stringer and skin and an attempt has been made to maintain as direct a load path as possible through the joint.

Figure 11 shows the fatigue test results for both of these joints and also the *S-N* curve of the average of all joints tested by the Royal Aircraft Establishment. Despite the contrasting types of the Bristol joints the fatigue lives differ only slightly and both are rather above average.

Figure 12 shows the fatigue test curve for the riveted joints used in the Britannia fuselage, the stress cycle being zero to maximum stress. Also shown, for comparison, is a similar American curve. The Britannia riveting uses a close tolerance rivet set in a close tolerance drilled, deburred and spin dimpled hole. The fatigue properties are relatively good. Many fatigue tests have been made, including tests with deliberate defects such as variations in pitch and margin, scratches and dimple defects. Surprisingly, the fatigue life has not proved sensitive to these defects.

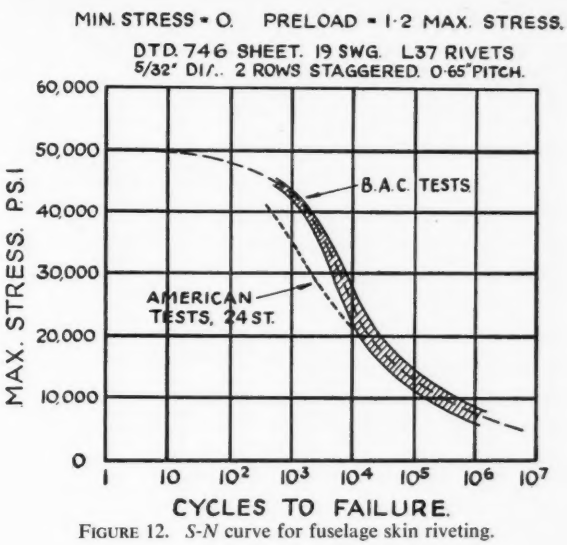


FIGURE 12. *S-N* curve for fuselage skin riveting.

Figure 13 shows a typical fatigue specimen of this joint.

Figure 14 shows a " drip stick " hole in the bottom surface of the Britannia wing, one specimen being without a reinforcing plate and the other with a plain flat riveted reinforcing. The test fatigue stress cycle was $10{,}550 \pm 3{,}420$ p.s.i. and the test results for two of each design are most interesting.

With Reinforcing	*Without Reinforcing*
$0{\cdot}405 \times 10^6$ cycles	$0{\cdot}602 \times 10^6$ cycles
$0{\cdot}360 \times 10^6$ cycles	$1{\cdot}187 \times 10^6$ cycles
Mean $0{\cdot}382 \times 10^6$ cycles	Mean $0{\cdot}895 \times 10^6$ cycles

Material D.T.D.746

The mean life with reinforcing plate is below average and this life is doubled when the plate is removed. The reason for this surprising result is that the reinforcing plate is poorly designed and introduces a greater stress concentration than that present due to the unreinforced hole. This result demonstrates an important detail design principle.

The low and medium strength aluminium alloys (D.T.D.364, D.T.D.746, D.T.D.710, L.65, etc.) give slightly higher fatigue stresses for a given life than the

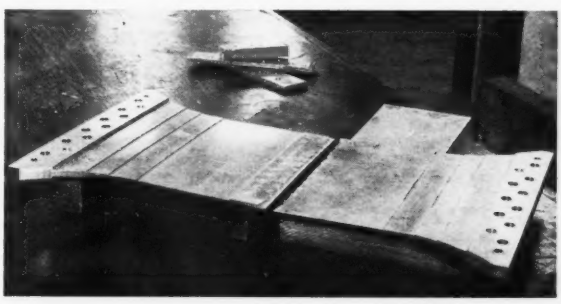


FIGURE 13. Britannia fuselage riveting test specimen.

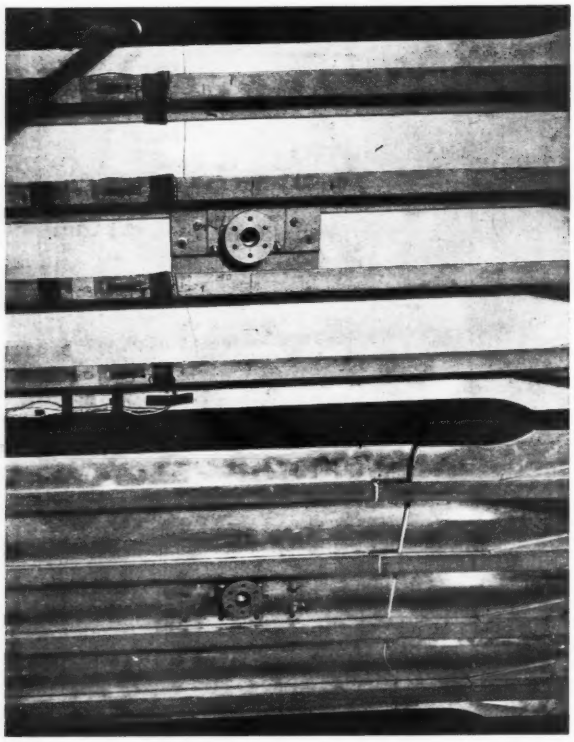


FIGURE 14. Britannia bottom wing skin drip stick hole.

high strength alloys (D.T.D.363, D.T.D.683, D.T.D.687, etc.). They are also less notch sensitive and have better crack propagation properties and should be chosen for applications where fatigue is important.

It is important that bolts be pretensioned to a proper level by controlled "torquing" in fatigue applications, particularly where the bolts are in tension, when significant improvements in fatigue life can be obtained. When bolts are in shear, better fatigue life is obtained by the use of interference fits or slight taper to expand the bolt into the hole.

A topical detail in relation to good fatigue design is that of the window shape for a pressure cabin. In this particular 2 : 1 stress field, a square window with well rounded corners gives a stress concentration of approximately 3. An elliptical shape, 2 : 1 proportions with the major axis vertical, reduces the stress concentration to $1\frac{1}{2}$, but if the ellipse is placed with the major axis along the fuselage the stress concentration is increased to $4\frac{1}{2}$. These factors, as quoted, ignore the effect of the radial load on the window, and also that of the window frame.

Figure 15 shows the peripheral stress distribution around a Britannia escape hatch as measured by electrical strain gauges placed between the frame rivets, about 0·9 in. from the edge of the cut-out. The contributions due to pressure loads, level flight loads and 10 ft./sec. gusts are shown and it will be seen that the maximum value occurs at about 60° from the horizontal axis. The variation around the periphery is, however, not large and the objective of a neutral hole has been reasonably achieved. It may be of interest to note that approximately 3,000 strain gauges have been applied to the specimen at the R.A.E. in this type of investigation.

One great difficulty in obtaining and using fatigue strength data from tests is that of scatter. The normal practice with joints is to test 4, or possibly 6, identical specimens for each loading condition. This is a heavy task, but even so, the scatter being high as it normally is, this number of tests will only allow a reliable mean value to be obtained and the scatter has to be obtained from other general test data.

In the case of Britannia fuselage riveting the scatter range for some 50 tests is approximately 3-1 and this is unusually good, a range of 10-1 being not uncommon.

This large and variable scatter makes the statistical problem of determining realistic factors of safety extremely difficult. It has to be borne in mind that the aircraft structure comprises many different detail features with different numbers of each detail per aircraft, different loading conditions and different mean lives and scatter values. The large scatter is a point of criticism of full scale fatigue testing such as the "tank" test. The expense of the test only allows one specimen to be tested and, as one result has little statistical significance, the factor of safety to be used with it is largely a matter of opinion. In these circumstances it is easy to specify a large factor of safety, usually between 5 and 10, but not so easy to sell an aeroplane with the "safe limit" restrictions which follow from these large factors.

Figure 16 attempts to illustrate the relative importance of some of the loading conditions which have been discussed, from the point of view of fatigue strength. The damage ratio (n/N) is used as a parameter in this assessment.

With regard to gusts, the value of 0·3 is reasonable, corresponding to cruise at 20,000 ft., but the same aircraft cruising at 8,000 ft. gives a value of 1·0. In

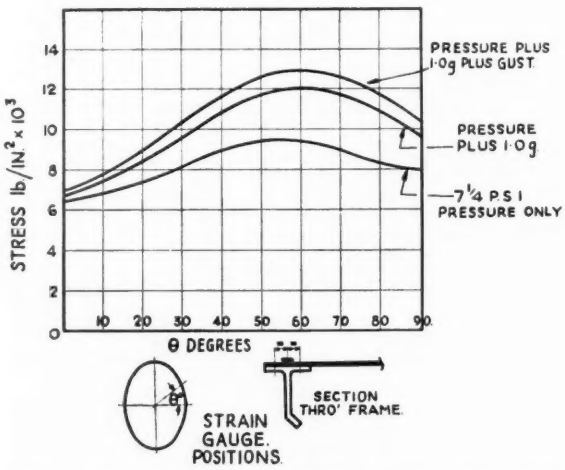


FIGURE 15. Britannia 100 pressure cabin strain gauge measurements at escape window (all gauges are endload measuring, around periphery).

the latter case, either the aircraft would be limited to say a 10,000 hour life, or else the stress level in the wing would have to be reduced by modification.

It is interesting to note that the damage due to 1·0*g* loads is very nearly as large as that due to gusts at 20,000 ft. The effect of flap loads on the rear spar shears is also of the same order.

The effect of gust loads on fins can be relatively large as indicated by the damage ratio of 1·0. The frequency of gust loads on fins has been shown by flight measurements to be the same as for wings and tailplane, but the fatigue stresses will be comparatively higher if the static strength is based on the 50 ft./sec. gust case.

With regard to cabin pressurisation loads, a working stress of 13,000 p.s.i. gives an acceptable damage figure, whereas, at 20,000 p.s.i., the damage is too high. It should also be noted that these stresses of 13,000 or 20,000 p.s.i. must include the effect of stress concentrations such as occur at doors, windows, escape hatches, and so on. Thus, if by good design these stress concentrations can be kept at about 1·2, then the corresponding general hoop stress figures are 11,000 p.s.i. and 17,000 p.s.i.

The damage figure for the undercarriage is too high and would indicate either a life restriction or modification, and this would be even more true of the hydraulic jack.

The figure quoted for the engine mounting is satisfactory, although this is not always so in practice. Both engine mounting and propeller fluctuating stresses are lower with turbine installations than with reciprocating engines.

These examples are somewhat over-simplified but the general indications are believed to be valid.

Any complete analytical assessment must make use of the Cumulative Damage Theory, the equation for which is given in Fig. 2. This theory is the subject of some controversy and cannot be taken as always applicable. Attempts to substantiate the theory by suitable test programmes have been made, but with varied success. The current trend is not to use this analysis, but to incorporate the varied loading cycles into the fatigue test, *i.e.* to do a " programmed loading " test, instead of separate tests at constant amplitude. There is some test evidence for believing that the more complicated test procedure will not only give a more accurate result but will also reduce test scatter.

The current practice in detail fatigue testing is to apply a preload equivalent to 2·0*g* before carrying out the fatigue loading. This is, in fact, the first step towards mixed cycle loading and it does seem to reduce scatter; in fact that is the reason for the practice.

Another factor in fatigue strength assessment is that of time, or frequency of loading. The corrosive effect of the environment, be it air, sea water, hydraulic oil or condensation, is important on the aircraft because of the long elapsed time involved. This can give rise to " corrosion fatigue " and a lower life than would otherwise be achieved.

In contrast to this, fatigue test machines are usually

FATIGUE LOADING CONDITION	STRESS CYCLE P.S.I.	NUMBER OF LOAD CYCLES IN 30,000 HOURS n	CYCLES TO FAILURE N	FATIGUE DAMAGE RATIO n/N
1·0g WING LIFT	−2,000 +14,000	10^4	5×10^4	0·2
WING 10 FT./SEC. GUST				
CRUISE AT 20,000 FEET	±3,500	2×10^5	6×10^5	0·3
CRUISE AT 8,000 FEET	±3,500	6×10^5	6×10^5	1·0
FIN 10 FEET/SEC. GUST CRUISE AT 20,000 FEET	±4,600	2×10^5	2×10^5	1·0
REAR SPAR SHEAR DUE TO FLAPS	0−10,000 (SHEAR)	10^4	5×10^4	0·2
CABIN PRESSURISATION LOADS	0−13,000	10^4	10^5	0·1
	0−20,000	10^4	2×10^4	0·5
UNDERCARRIAGE LANDING LOADS	0−20,000	10^4	2×10^4	0·5
HYDRAULIC COMPONENT PRESSURE LOAD	0−25,000	10^4	10^4	1·0
ENGINE MOUNTING TUBE	±4000	3×10^6	∞	—

FIGURE 16. Fatigue damage ratio for various loads.

run relatively fast, therefore the elapsed time is short and the corrosion effect is not representative even though the correct medium is provided. When testing fabricated joints at high frequency, however, fretting corrosion can occur between the separate joint elements and can reduce the test fatigue life.

In practice we prefer to test at moderate frequencies, *i.e.* hundreds of c.p.m., rather than thousands, even though the elapsed testing time is often embarrassingly large.

4. Inspection and Maintenance

Because of the difficulties of designing so that fatigue cracks never under any circumstances appear, inspection has to be based on the assumption that a crack may occur. It is, therefore, important that inspection periods be based upon an assessment of this possibility and that access is possible to the structure so that inspection can be carried out and a crack found before it reaches a critical length. As fatigue cracks are often difficult to find, even with a magnifying glass or other special aids to inspection, the accessibility must be good, particularly in the case of primary structure. External inspection must also be thorough in finding structural damage such as dents, scratches, holes or tears, whether from stones or ice, in use, or from careless damage from ground equipment and tools by ground staff. It is quite obvious that a dent or scratch can easily produce a stress concentration greater than that designed into the structure and can, therefore, start an early fatigue crack.

These possibilities of operational damage which cannot be assessed in design are also additional difficulties in the problem of predicting fatigue life.

Where controlled bolt torquing or interference fit taper bolts are used it is also vital that the recommended values be checked and maintained during service.

When fatigue cracks are found then a temporary expedient is often to "stop" the crack by a small drilled hole. This achieves its object for a short time by replacing the high stress concentration of the crack with the lesser concentration due to the hole. The difficulty with this practice is that of locating the true end of the crack. It is obviously important to have the hole slightly off the end of the crack, rather than run the risk of drilling the hole in the crack itself. Fatigue cracks are normally repaired by fitting reinforcing plates as early as possible but it is important here to remember the example of the drip stick hole.

If the repair scheme itself introduces a high stress concentration factor then a new crack will almost certainly start at an early stage. As much care and skill is therefore necessary for the design of the repair scheme as for the initial design itself.

5. "Fail Safe" Design

As already mentioned, the difficulty of predicting safe fatigue life with the necessary confidence is enormous unless excessive conservatism is practised. Additional safeguards so that a fatigue crack does not cause catastrophy are therefore necessary. This philosophy is a basic principle of airworthiness and is already applied to other aspects of the aircraft, *e.g.* the use of multi-engines, duplicated hydraulic systems, safe electrical and auto-pilot failures, and so on.

One of the first steps in applying this principle to that of structural failure by fatigue is to study the rate of growth of cracks and to establish the factors which govern whether a crack grows slowly or catastrophically. If the factors can be fully established then it should be possible to design so that "fast" or catastrophic cracks do not occur, either not at all, or at least by specifying inspection periods so that repair action is taken before the critical "fast" crack length is reached.

A considerable amount of work on this problem has already been done at Bristol, mostly under conditions of static loading of flat specimens of different materials, but also under fatigue loading conditions for comparison.

Figure 17 compares these static and fatigue results and shows maximum stress (*i.e.* mean+alternating stress) in the fatigue tests, against crack length at which fast failure occurs. It is reasonably demonstrated from these tests that the relationship is the same, whether the loading is static or fatigue.

Figure 18 gives the results of the fatigue tests in more detail and shows the development of the fatigue crack from the initial slit until fast fracture occurs.

Figure 19 shows the results of the static tests and compares the crack propagation rate of different aluminium alloy materials. The specimens shown here were 10 in. wide but tests have also been made on 20 in. and 40 in. widths.

The effect of crack "stoppers" has also been investigated in this type of test, flat reinforcing strips being riveted or "Reduxed" to the specimen which is slit and loaded so that a fast crack is induced. These strips were effective in arresting the cracks, but loading was subsequently continued to failure. The failing stresses

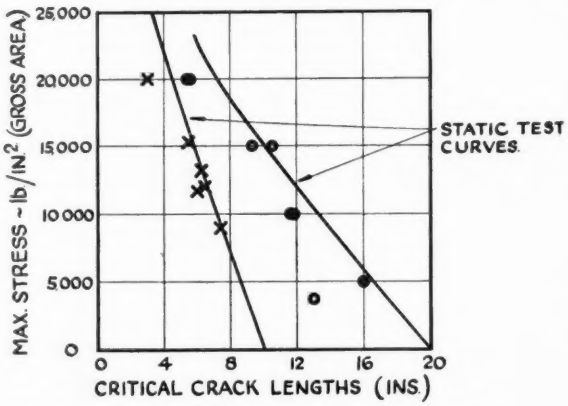


FIGURE 17. Comparison of fatigue and static critical crack lengths.

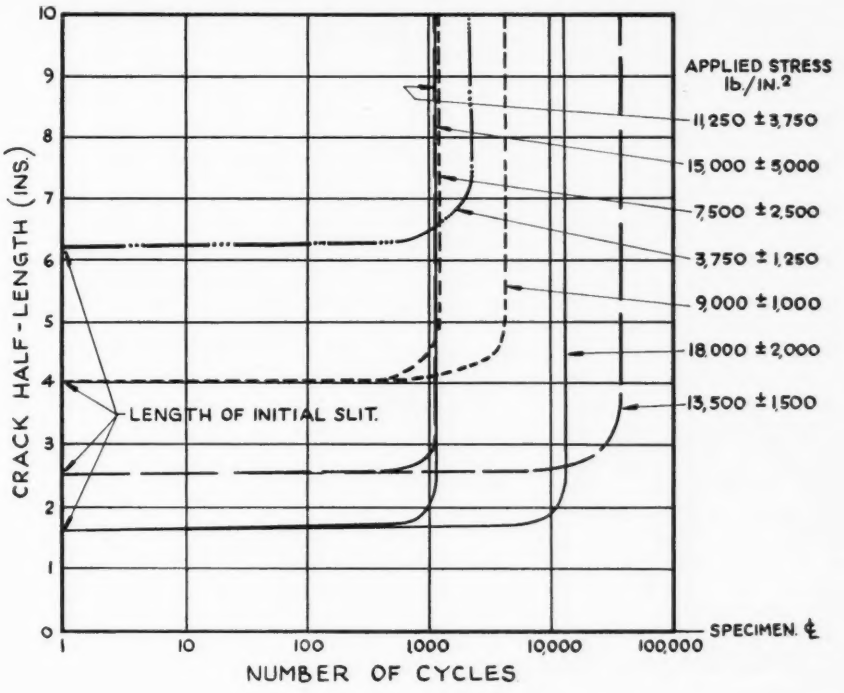


FIGURE 18. Fatigue crack propagation tests.
Material—19SWG. D.T.D. 746 sheet.
Specimen—20 in. wide × 40 in. long.

in these tests are also plotted against the distance between "stopper" strips and an indication of the improvement can be seen, the "Reduxed" strips being most effective. Fig. 20 gives details of these experiments.

Another approach to this problem of "fail safe" design is to provide multi-structural load paths so that even though a fatigue cracks starts, and even reaches "fast crack" proportions, and severs one of the load paths, an alternative load path provides sufficient strength to prevent immediate catastrophic failure. Dr. Williams of the Royal Aircraft Establishment has suggested design along similar lines and the N.A.C.A. are also doing some experimental work. Fig. 21 shows some of the N.A.C.A. results.

The tests are on pressurised cylinders, 30 in. diameter with stringers, frames and small cut-outs. Fatigue cracks are induced by torsional loading and the failures have been studied in relation to the ratio of frame area to skin area between frames. The results are few in number, but they do tend to separate into two areas of explosive and gradual failures on this basis. The full line on the graph has been suggested by the N.A.C.A. as a simple criterion of design and assumes that the frame area is sufficient to take all the load even though the skin has failed, and also that the maximum

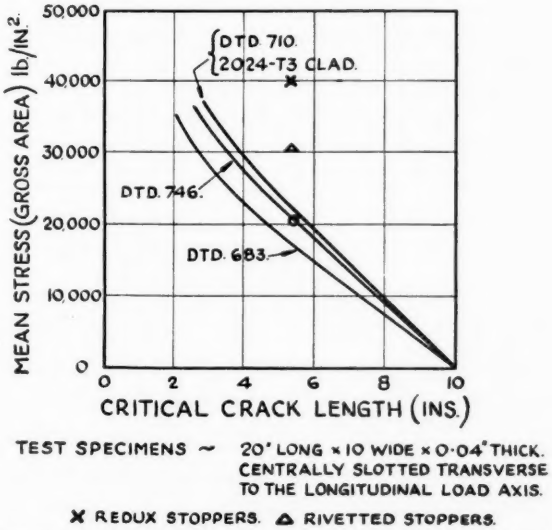

MEAN STRESS (GROSS AREA) lb./IN.²
D.T.D. 710.
2024-T3 CLAD.
D.T.D. 746.
D.T.D. 683.
CRITICAL CRACK LENGTH (INS.)
TEST SPECIMENS ~ 20" LONG × 10 WIDE × 0·04" THICK. CENTRALLY SLOTTED TRANSVERSE TO THE LONGITUDINAL LOAD AXIS.
✕ REDUX STOPPERS. △ RIVETTED STOPPERS.

FIGURE 19. Relationship between mean stress and critical crack length.

	Specimen	Mean stress at failure p.s.i.
1	Plain	21,000
2	Riveted Stoppers	31,250
3	Riveted Stoppers	31,000
4	"Reduxed" Stoppers	40,500

1. Plain 40 in. × 20 in. × 0·04 in. D.T.D. 746. 5½ in. initial slot.
2. 40 in. × 20 in. × 0·028 in. D.T.D. 746. Stopper strips 2¼ in. × 0·08 in. D.T.D. 746, at 10½ in. pitch. Riveted to sheet. 5½ in. initial slot, aligned with rivets.
3. As 2 but initial slot aligned between rivets.
4. As 2 but stopper strips "Reduxed" to sheet.

FIGURE 20. The influence of "stopper strips" on fast fracture.

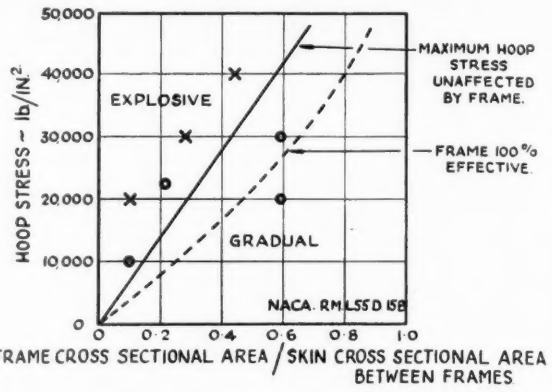
hoop stress is unaffected by the presence of the frames. If the hoop stress is uniform in skin and frame then the dotted line would represent this criterion.

At Bristol flat plate work is being extended to the three-dimensional problem by testing 44 in. diameter cylinders and ultimately to full scale 12 ft. diameter specimens.

All of this work so far is only sufficient to indicate profitable lines of development. It is, as yet, too early to say that either the problem or the solutions are fully understood.

An interesting comparison of existing design practice can be made from the " fail safe " point of view. Considering first a wing box structure with skin stiffened by close pitch spanwise stringers, any chordwise fatigue crack in the skin will almost certainly be arrested by the stringers and detection and repair action will be possible before any danger arises.

In contrast to this, some pressure fuselages have frames which are attached to the inside of the longitudinal stringers and not directly to the skin. The maximum principal stress is probably the hoop stress and fatigue cracking would therefore be longitudinal, but such cracks will not be arrested by the frames. Complete rupture could take place in this case before detection of the fatigue crack.



TEST RESULTS FOR 2024-T3 ALUMINIUM ALLOY PRESSURIZED STIFFENED CYLINDERS.

X FAILED EXPLOSIVELY. O FAILED GRADUALLY.

FIGURE 21. Simple failure criterion for stiffened pressurised cylinders.

6. Conclusion

The following is a summary of my personal recommendations for a philosophy of design for fatigue.

(*i*) Carry out an analytical study of the operating loading conditions of *all* primary components.

(*ii*) Give careful consideration to the choice of material and stress level, using the *S-N* data most relevant to the particular application and carrying out tests where suitable data is not already available.

(*iii*) Simplify the design of structure to the greatest possible extent and pay careful attention in detail design to minimising stress concentration factors. This ensures that fatigue stresses can be predicted with the maximum degree of confidence.

(*iv*) By careful design and choice of stresses and materials ensure that crack propagation rates are low and that fatigue failures will not be catastrophic.

(*v*) Carry out extensive fatigue tests of all details where fatigue damage is predicted as significant.

(*vi*) Confirm by flight strain gauge tests the assumed fatigue loading data and also strain gauge or stress lacquer static test specimens so that *all* points of stress concentration are obtained.

(*vii*) Use counting accelerometers and/or strain gauges in service and choose the operating conditions so that the best compromise between fatigue and other considerations is obtained.

(*viii*) Ensure a high standard of maintenance and inspection so that ground handling damage is minimised and fatigue and other flight damage detected and repaired while still safe.

Finally, I am reasonably sure that, even though such design-development procedures may be expensive, a safe long life aeroplane can be achieved from the fatigue point of view without any very significant weight or operating economic penalty. It is principally a matter of recognising the problems and doing the necessary work.

Aircraft Strength Testing

by

P. B. WALKER, C.B.E., M.A., Ph.D., F.R.Ae.S.
(*Head of Structures Department, Royal Aircraft Estabment*)

1. Introductory

The part played by strength testing in establishing structural integrity and efficiency is well known to aeronautical engineers. In principle, the great advances made in structural theory and stressing methods should lessen the pressure on strength testing facilities. In practice, things do not seem to work out this way. For this there appear to be two reasons. The first is the

continuous change in aircraft structural design to meet new or more exacting operational roles. The second is the demand for still lighter structures without prejudice to safety. Strength testing, therefore, is as necessary as ever it was if the best results are to be obtained.

For a great many years structural strength testing meant just static strength testing. This is no longer true, since for many types of aircraft fatigue testing has become at least as important as static testing. Furthermore, high speed supersonic aircraft present new problems in both forms of testing but at elevated temperatures.

The ground for discussion therefore extends over three distinct fields, namely: —

(*a*) Static testing, *i.e.* with a single load application direct to destruction;
(*b*) Fatigue testing, *i.e.* with repeated load application;
(*c*) Thermo-structural testing, *i.e.* testing at varying and elevated external temperature.

It is of interest to note that so far as technique and experience are concerned these three items represent roughly the past, present and future. There are now many years of past experience behind static strength testing; we are only just learning the art of fatigue testing; while thermal testing is still a project that lies mainly in the future.

In the discussion which follows it is intended to deal mainly with the broader policy issues, and the actual technique comes into the picture only when it is still novel and has policy implications. Static strength testing is considered from the standpoint of its contribution to safety and efficiency (Section 2), and trends of weakness in design are then discussed (Section 3). Fatigue is also considered from two points of view, although these are quite different from the previous ones. Consideration is first given to the fatigue hazard (Section 4) since it is clear that one of the greatest difficulties of the designer is to decide when fatigue tests are necessary. This is followed by a brief review of fatigue testing in relation to design (Section 5).

Finally, the testing of high speed supersonic aircraft is discussed (Section 6). Technique inevitably comes into the picture here since there is the new problem of reproducing, in the testing laboratory, the complex thermal conditions that occur in high speed flight. The opportunity is taken to refer to preliminary work which gives promise of a successful solution to this new strength testing problem.

2. The Value of Static Strength Testing

The aircraft industry now expends considerable effort on the static strength testing of prototype structures. The work is usually done in the most critical stage of a new design, when time is precious. Furthermore, static testing adds appreciably to the cost of a new aircraft type, the largest item being the cost of test specimens, although charges on labour and equipment are not insignificant. In the light of these facts it is necessary to make from time to time a careful assessment of the benefits that are obtained from a liberal testing policy.

Static strength testing may for practical purposes be divided into two parts:

(*a*) Component testing;
(*b*) Major strength testing.

" Component testing " scarcely needs to be defined but " major strength testing " has acquired a special meaning. In principle the term is used for a test made on a complete aircraft structure, but in practice this is allowed to degenerate into the separate testing of large portions of the aircraft such as the complete wing system with part of the fuselage in position, or the complete fuselage with part of the wings in position. The distinction between the two types of testing is not as simple as it might appear: there are differences in procedure in addition to differences in the size of the elements tested.

Component testing is very largely a domestic concern of the designer. It is less concerned with approval of a component than with checking the design theory and methods that have been used. When methods are well-tried and certain, testing is not essential. Furthermore, the design of a component may be modified in the light of knowledge gained in the test, so that the component is not tested in its final form except as a part of the main structure.

Major strength testing raises wider issues since it is not only much more expensive than component testing but is also the final check on whether the structure can be accepted as satisfactory. It is mainly in this field that the benefits obtained have to be weighed against the cost incurred.

In 1949, the author wrote a paper entitled " Records of Major Strength Testing[1]. Ten years of testing experience throughout the British aeronautical field was drawn upon. The first conclusion reached was that major strength tests were essential to safety. About half the structures as originally designed failed to reach the standard of strength laid down in design.

The general outlook, however, was brightened considerably by a further conclusion. Most of the aircraft that failed prematurely reached the required standard after one or two simple modifications. These modifications, moreover, usually incurred only a small increase in weight, and the modified aircraft were among the more efficient in economy of structure weight. Thus it was concluded that major strength testing made a significant contribution to structural efficiency as well as to safety.

It was further suggested, in the paper referred to, that some designers were deliberately taking risks of a premature failure on test in order to save weight, secure in the knowledge that ultimate safety was ensured by the final test.

There is now seven more years' experience to draw upon. Detail statistics are not published but it is clear beyond doubt that the proportion of initial premature failures has not declined. This confirms the value of strength testing for safety but goes much further. In spite of greatly extended knowledge of structural theory, backed by stronger and more experienced design staffs, with all the modern aids in the way of calculating machinery, the proportion of initial failures has not declined. It is clear, therefore, that the improvements in

design methods and organisation have been directed largely towards saving weight. The new philosophy of taking risks in initial design is in point of fact now widely accepted*.

3. Sources of Structural Weakness

The benefits of static strength testing are not confined to the particular aircraft actually tested. From the experience obtained from all the aircraft tested it should be possible to find the danger points so that some of the mistakes may be avoided on future designs. It is not practicable to give a detailed account of past failures individually but there are certain broad conclusions which may be drawn.

Mention should be made first of the human error. There is always a possibility of an error in calculation, or a gross error of judgment in selecting design methods. It is not appropriate to discuss this aspect in this paper, since the matter is best dealt with by the designers themselves. It should be mentioned, however, that over the past five years the author has no knowledge of premature failures that could have been prevented by careful checking or by reasonable foresight.

The great majority of premature failures appear to fall into two classes:

(*a*) structural instability;
(*b*) stress concentration.

The characteristics of a stability failure is that little or no advance warning is given of impending failure. At one loading the structure may appear satisfactory on test and then collapse completely when the load is increased by only one or two per cent. A few years ago one aircraft failed in flight suddenly and disastrously during a manoeuvre. The cause was structural instability, and records showed that practically the same manoeuvre, probably only slightly less severe, had been carried out at least fifty times without any adverse consequences. There are indications that the designer is most likely to have trouble with a complex loading system in which some of the loadings might normally be regarded as secondary.

The possibility of structural instability is one of the main reasons why proof tests of the non-damaging type are unsatisfactory. If a strength test is made within the elastic limit there may still be a considerable reserve of strength provided the failing point is not governed by stability. If stability failure is the danger, however, there may be virtually no reserve of strength at all.

The second general cause of premature failure—unexpectedly high stress concentration—may be associated with all the problems of stress diffusion. The possibility has to be faced that it may never be safe to rely entirely upon theoretical calculations to reveal the existence of all local concentrations of stress or, where they are revealed, to indicate their full magnitude.

There are two interesting sidelights on the stress concentration issue. The first concerns strain gauges. Extensive strain gauging is more valuable than is generally realised. In many cases comprehensive strain gauging may reveal excessive loading before there is any risk of failure. It is then possible to modify the structure and avoid unnecessary destruction and waste of time.

The second sidelight concerns fatigue testing. A fatigue test is far more effective at detecting stress concentrations than is a static test. Where fatigue tests are required anyway, therefore, it may be possible to dispense with major static testing. It is necessary to be certain that failure through structural instability will not occur, however, since fatigue tests can throw no light at all on this aspect.

4. The Fatigue Hazard—Deciding When Fatigue Tests are Necessary

The amount of fatigue testing now required in aviation has become considerable. In the transport field—civil and military—the pressure on testing resources is now greater than that produced by static testing. At the present time fatigue tests are required whenever there are grounds to suspect that there is danger, since theoretical methods cannot be relied upon to give more than a rough approximation to the fatigue characteristics of the structure, and the chances of error are greater than in calculations of static strength.

From the standpoint of general testing policy there are two distinct issues which the designer has to face. He has to decide what tests, if any, are necessary, as well as how the testing should be carried out when it is necessary. It is proposed to deal first with the need for testing. It is generally recognised that fatigue has to be extensively investigated for all transport aircraft, but other types are not necessarily immune.

There are three main contributors to fatigue, namely:

(*a*) gusts;
(*b*) cabin pressurisation;
(*c*) manoeuvres.

All may be present in some degree but usually one is the predominating element for a particular part of a particular aircraft.

Gusts have long been recognised as a primary hazard for transport aircraft. It is owing to gusts that practically every transport aircraft has a life limitation imposed. Wings are the most vulnerable but the tail surfaces are also exposed to some danger. The tailplane danger may well increase as wing design improves and longer operating lives are allowed. At the other extreme are fighter aircraft, which still appear relatively immune to the fatigue effects of gusts. This immunity is attributed, first, to the high static strength provided for manoeuvres and, secondly, to the relatively short life required. Bombers fall into an intermediate category. One factor in favour of bombers is the experience being obtained in design of transports, the benefits of which tend to be infused automatically into bomber design.

Pressure cabin fatigue is another hazard to transport aircraft. Although there is normally one cycle per flight, it is a very severe cycle in terms of stress, since

*It is of interest to note that almost exactly the same conclusion appears to have been reached quite independently in the U.S.A.

the peak of the fatigue loading is also the maximum operating load. Considerable attention has recently been focused on pressure cabin fatigue, but the design difficulties do not appear insuperable now that the danger is known. The general position of fighters and bombers in relation to pressure cabin fatigue is still uncertain. The number of flights required within the working life is likely to be considerably less than for transport aircraft, but there is a possibility of several pressure changes in any one operational flight.

In most cases the effect of manoeuvring loads is to aggravate the effects of gusts and cabin pressure already mentioned. There is at least one important exception: ground attack fighters have their wings heavily loaded each time a pull-out manoeuvre is made. Owing to the nature of the operational role this manoeuvre may be frequent and fatigue is then a definite possibility. The fatigue testing of ground attack fighters therefore always requires serious consideration and may often be necessary.

5. Fatigue Testing in Relation to Design

When consideration is given to the actual process of fatigue testing it is found that, as for static testing, the tests fall into the two categories: component testing and major testing of complete aircraft or large units such as wing systems and fuselages. Here the similarity with static testing ends, however, since component testing has an even more vital contribution to make. Owing to scatter, life predictions require the testing of several identical specimens. Major fatigue tests are extremely costly and cannot be repeated as a routine, and hence repetition testing has to be confined to selected components that are regarded as critical.

It is undesirable, moreover, that a major test, even when carried out only once, should be used for discovering fatigue weakness which could reasonably have been established earlier in a component test. Major tests are required for quite different reasons. In particular they are a means of discovering weak places which could remain unsuspected without a comprehensive test. For the tests to be effective in this way it is necessary for repairs to be made after each failure and the test continued for a long time. Another important application of major fatigue testing is for the study of crack propagation. Cracks in wing skin, for example, are not necessarily catastrophic in the early stage, and in assessing the danger it is necessary to know how rapidly a crack extends to catastrophic length.

The technique for testing wings and tail surfaces is now well established. The earlier method of testing by vibration at the natural period is giving place to direct loading by hydraulic jacks. For large wings and any other components with a low natural frequency, excitation is very difficult and unreliable so that direct loading is the more practical method.

The technique for pressure cabin testing is relatively new, and was first applied on a comprehensive scale in the Comet investigation[2]. Water is normally used as the pressurising medium owing to the explosive damage caused by failure in an air test. There is a general tendency to lay stress on the danger of air tests, but even more important are the difficulties of detecting the origin of failure amidst the wreckage and of making repairs for continuation of the test. There are reasons to suppose that manoeuvring loads in the air and on the ground reduce the life of pressure cabins beyond that appropriate to the pressure cycle alone. It is therefore desirable to load the wings and fuselage to represent lift and gust cycles, and possibly other flying loads as well. This makes the test a major task, requiring virtually a complete aircraft; but most of the technical difficulties have been overcome, and the methods are now being applied to several transport aircraft.

6. Thermo-Structural Testing

With the prospect of supersonic speeds at high Mach numbers some entirely new problems in structural testing are presented. The mechanical loading system has to be combined in some way with the complex thermal loading system. Both static and fatigue effects may need to be investigated.

The effects of heat generation and high temperature have been analysed in an earlier paper by the author[3]. In the main these effects comprise the deterioration of the properties of the structural material and the introduction of thermal stresses.

The thermal conditions over the surface of a supersonic aircraft follow a complex pattern, temperature varying with time and position on the surface. The basic data have to be provided by aerodynamicists, and the task of the structural engineer is to reproduce the conditions in the laboratory.

There are many detail problems but the most difficult is to provide a suitable heat source. For this heat source there are three essential requirements:

(*a*) The rate of heat generation must be adequate;
(*b*) The heat output must be readily and rapidly controllable;
(*c*) Heat for different parts of the surface must be separately controllable.

As regards the rate of heat generation, a supersonic aircraft is a very efficient generator of heat. The actual rate depends on altitude as well as Mach number, but for a rough indication we may take 20 kilowatts per square foot of surface as the maximum appropriate to a Mach number of 4 at 50,000 ft. Rapid response to control is essential if the complex time-temperature pattern of actual flight is to be simulated. The heating system must have, in effect, a low thermal inertia.

There are many systems which satisfy the first requirement, for a high rate of heat output. Most of them fail, however, through having too high a thermal inertia, and thus being insufficiently responsive to control. The main exception is the quartz infra-red lamp which has now been developed to a stage where it meets all likely requirements for some time to come. A heat input to the surface of 20 kilowatts per square foot is readily attainable while 40 kilowatts is likely to be reached eventually. An electronic controller has been developed which makes the surface follow the prescribed thermal pattern in relation to time. Large numbers of

lamps are required for an aircraft structure, giving the advantage that different parts of the structure can be controlled separately.

The most important alternative to infra-red heating is electromagnetic induction. The main advantage of induction heating is the high rate of heat input that is possible, which greatly exceeds the capacity of infra-red lamps. There is, in fact, no foreseeable limitation to its use as the speed of flight increases indefinitely.

Induction heating, however, has serious disadvantages at present. It is much less amenable to control than are infra-red lamps, not as regards time variation of heat input but as regards variation over the surface of the structure. Furthermore, the rate of heat production depends upon the electrical and magnetic properties of the structural material—a serious objection if dissimilar metals such as steel and light alloys are used in the same structure. The electrical and magnetic properties of material, particularly of steel, moreover, change appreciably with temperature and this again makes control of heat production difficult.

It is not improbable that research will in time overcome these difficulties. One adverse characteristic, in fact, has already been dealt with; this is the tendency for heat to be produced within the material and not outside as is required to simulate flight conditions. By use of a very high frequency the heat production has been confined to a thin outer layer, say one thousandth part of an inch thick, from which region it is conducted inwards realistically.

The situation now is that we can already envisage realistic thermo-structural tests on a large scale with infra-red lamps as the source of heat. Small-scale experiments have already been made successfully and tests on a larger scale are in the course of preparation. Meanwhile work is proceeding on induction heating as an alternative, with possibilities of application at speeds of flight well beyond those covered by infra-red heating.

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Summary of Discussions

by

ANTHONY J. BARRETT, M.Sc. in A.E., B.Sc.(Eng.), M.I.A.S., A.F.R.Ae.S.
(*Head of Structures Group, Technical Department, Royal Aeronautical Society*)

1. Introduction

The Society's All-Day Discussion on Aircraft Design Philosophy was extremely well supported and at one stage there were more than 350 members and visitors present. As is inevitable on these occasions there was insufficient time available for all those who wished to make a contribution to do so, even though the four lecturers had reduced their contributions to a bare minimum by presenting summarised versions of their papers.

With such an all-embracing title as Aircraft Design Philosophy it was obvious that some main channel of exploration would have to be chosen; that which evolved during the planning of this event was structural safety, as will be apparent from the discussion. The preparation of a summary of discussions presents a number of problems. The most obvious pattern to follow was Mr. W. Tye's report of the Society's Discussion on Fatigue which took place in March, 1953. (*See* the JOURNAL of September, 1953). Readers of this summary are recommended to look once more at the report of this earlier event, for there are many interesting comparisons to be made and many trends to be discovered in the two and a half years between these two discussions.

The majority of speakers dealt with matters concerned with, or related to, the still present problem of aircraft structural fatigue. One might have expected that given the opportunity to think aloud, which is the usual manifestation of the aircraft designer's philosophy, he would choose those problems most pressing and those upon which he wished to hear the views of others.

Although the emphasis was on fatigue, contributions ranged over a very wide field and the author has had to take upon himself the responsibility for choosing those points which appeared to him to be of the greatest interest and importance. No attempt has been made to follow the original order of the discussion because many points raised in the four separate sessions were interrelated and arose again during the general discussion period at the end of the day.

2. Design Requirements

2.1. NEGATIVE "*g*" REQUIREMENT FOR CIVIL AIRCRAFT

The reasons for civil aircraft to be capable of executing manoeuvres with relatively severe negative normal accelerations were queried. The case for such a requirement was not clear as an airline pilot would never go below zero normal acceleration except in the greatest emergency. It was suggested that the sole reason for this requirement was the inverted flight case which, surprising as it may seem, had actually been encountered on a foreign airline. Although justification of a requirement might seem slender if based on one incident, the further point was made that malfunctioning of automatic pilots must always be borne in mind and

that an aircraft must be capable of withstanding excessive normal accelerations of either sign under these conditions. Compression structure on an aircraft was also capable of carrying a certain amount of tension loading, and *vice versa*, so that the imposition of the requirement probably caused little increase in structural weight.

2.2. MANOEUVRES FOR MILITARY AIRCRAFT

Manoeuvres in general, as specified in official documents, came in for a good deal of criticism and in particular the " fish-tail " yawing manoeuvre and the " rolling pull out."

Although the fish-tail manoeuvre was necessary for ground attack or torpedo-carrying aircraft it was suggested that the less skilled pilot of other types of military aircraft would use the manoeuvre in combat. There was reason to believe that the more rigorous selection of personnel by the military authorities could go some way to allowing the assumption of closer margins at the design stage with respect to the manoeuvres which would be attempted in service. This seemed to offer a reasonable solution to a problem which, if allowed to exist without discrimination to the type of aircraft involved, could inflict severe weight penalties.

The position with the rolling pull out was in many ways similar, for it appeared possible in many cases for a pilot to apply considerable aileron deflection before the roll was developed with the consequence of excessive loads. The possibility of building up the control forces to prevent pilots putting on excessive loads did not seem to be a very adequate solution as it was suggested that if control forces were put up it was still possible, by the use of trimmers, to put the loads on anyway. *g*-restricters were mentioned as a possible solution, although there was still much to be done to ensure that these devices were capable of working safely and efficiently. They did hold out, however, the possibility of saving a great deal of structural weight on the highly manoeuvrable aircraft.

To conclude this part of the report on a somewhat happier note it was evident from the discussion that these matters were much under consideration at the present time by the authorities.

2.3. STIFFNESS CRITERIA

In the design of large high-speed aircraft it had often been found that stiffness requirements were more critical than those of strength. Not only were the present stiffness criteria out of date, but for many configurations they were difficult to interpret in view of the use of such terms as " mid aileron " and " equivalent tip." Whether or not these requirements were likely to be re-stated in time for them to be of any help seemed questionable and it was suggested that ultra-modern configurations, such as the short span delta, might cause strength requirements to be once again the more critical.

2.4. COMPARISON OF BRITISH AND UNITED STATES PRACTICE

A possible outcome of the Anglo-American Aeronautical Conferences is that discussions now seem fated to raise the comparison of British and United States practice. In the particular respect of flight loads it was noted that current American manoeuvre factors, for comparable large aircraft, were some $0{\cdot}5g$ lower than those specified by present British requirements. Was this a difference in basic philosophy or did it reflect upon air crew training? There being no representatives of the United States industry present we could only hope for a partial answer to this point. It was suggested that the greater man power and facilities available in the United States enabled the development of aircraft to a higher degree and at a greater rate. Weak points were thrown up by quicker building and testing and it was well known that the fully developed aircraft could operate with lower factors. Again, in the absence of a United States representative, the challenge that we in this country were more conscientious in meeting requirements of this type was unlikely to reveal whether or not this was in fact the case.

One further point in this comparison seemed to be very valid. In the United States efforts were being made to perfect power control systems, covering the complete flight envelope, so that it would be theoretically impossible to break up an aircraft by unintelligent manoeuvring.

3. Electronic and Mechanical Aids to Flight Safety

Throughout the day there were frequent references, both kind and unkind, to what have come to be known, in the brand of technical language peculiar to aeronautical engineering, as " black boxes." In particular the *g*-restricter came into the discussion on a number of occasions. Although it was possible to consider the *g*-restricter as a device somewhere between the pilot and aircraft there was a strong feeling that any device should be regarded as an integral part of the aircraft. In this case one might start out by designing the aircraft with such poor control characteristics that the excessive normal accelerations could not be put on. There was the further danger of " feed back " through electronic devices causing instability. These points did not go unchallenged. It was pointed out that duplication could provide safety and further, in the absence of electronic devices, with their very short reaction time, the relatively slow reaction of a human pilot was such that instability could occur very easily in high-speed flight. The discussion on these matters concluded on a sobering note when it was asked whether the time to failure of these devices might not be less than the fatigue life of the structure in which they were employed.

4. Fatigue

4.1. GENERAL ASPECTS

The main discussion on fatigue was concerned with the concept of the fail-safe structure and the fatigue properties of materials, although there were a number of

contributions dealing with the effects of pre-loading and locked up stresses.

One striking example of pre-loading was quoted. It had been found by a United States company that hydraulic components, working at about 3,000 lb./in.^{2}, were subject to frequent fatigue failures. Pre-loading to several times the working pressure had eliminated these failures altogether. It was suggested that such simple remedies could be applied to many minor items other than main structures in which interest seemed to be centred, although the difficulty of specifying design lifetimes for minor items might be considerable.

Fatigue in its more human sense was also discussed. In general, despite structural fatigue troubles, only some 5 per cent. of accidents were attributed to structural failures while a far greater percentage were put down to pilot error. These errors were likely to have been caused by the inadequacies of the human pilot to respond sufficiently fast due to physical and mental fatigue.

4.2. THE FAIL-SAFE CONCEPT

Looking back to the report of the Discussion on Fatigue, held in March 1953, we find that there was then in the minds of some engineers in this country the idea of redundant "inspectable" structures which could fly until fatigue cracks started, as the initial cracks would not be catastrophic. Although on that occasion there were doubts as to the wisdom of the practice it was generally agreed that a move in the direction of such a type of structure would have advantages. The recent discussion could not be said to have reached a great deal of agreement on any aspect of fail-safe construction, save possibly that it was a difficult thing to design for and even more difficult to demonstrate in test.

There had been some considerable discussion on fail-safe structures before a definition of the term was called for. It appears that the expression was originally developed to describe switches and signals which failed in such a manner as not to jeopardise the safety of whatever mechanism or system they formed a part. That "fail-safe" was in many ways an unfortunate term was brought out, not only by the confusion as to what it meant, but also by its being composed of two terms which for years have been thought of as mutually exclusive. The term which had been previously used, *i.e.* "redundant inspectable structures" would seem to describe the type of structure which the enthusiasts of fail-safe wanted to achieve.

Assuming that in one of a number of discreet elements a fatigue crack had grown to the stage where it could be found on inspection, or where the element had failed completely, without affecting the immediate operational efficiency of the aircraft, what action should next be taken? Would it be sufficient in such a case to patch the member or would it be necessary to replace it completely? If the latter were the case, then the saving over the alternative procedure of estimating the life of the member and replacing it before the crack appeared might not be very great when the more elaborate inspection procedure for the "fail-safe" structure was taken into account.

If there were doubts on the economics of the idea there were even more doubts on the manner in which the safety of a fail-safe structure could be demonstrated on test and how a test could be related to actual operating conditions. For example, a component in which a fatigue crack had started might go on operating until a peak load was experienced, in a storm for example, at which time it would presumably fail, possibly with catastrophic results.

Although it was apparent that there were difficulties in the specification of, and design of, fail-safe structures there was little doubt that the philosophical basis for the idea was well understood, mainly because it had been practised for a number of years in other than structural applications. Apart from switches and signals already noted, engine and equipment design had never been on the basis of 100 per cent. reliability, as witnessed by the use of multiple engines and the duplication of other equipment. In contrast to this, structural design had been on a basis of little, if any, duplication and although the structures had been good, with minor failures creating no major hazards, it was now being realised that 100 per cent. reliability was not feasible and the possibility of parts failing must be accepted. Even so, the striving for as great reliability as possible must not be less urgent, there could be no slackening off in this respect, no more than had the engine designers and others ceased to expend their energies in achieving high reliability. It was noted that, even in the past, although no special effort had been made to produce fail-sale structures, there were examples which had been in operation for some considerable time. The Dakota was quoted as an example where fatigue cracks had occurred without creating a major hazard and where patching or replacements enabled these aircraft to continue their useful life almost indefinitely. This statement brought forward the interesting suggestion that a Dakota wing which had seen considerable service might be put through a strength test as a means of providing useful information for specifying tests for the demonstration that new structures were of the fail-safe type.

4.3. INTEGRAL CONSTRUCTION AND THE FAIL-SAFE CONCEPT

On a number of occasions during the discussion of fail-safe, references had been made to the integral type of construction. It had been well known for some time that the integral form of construction had much to offer in the way of time saving and possibilities of producing good aerodynamic surfaces. Further, having fewer stress raisers it would seem to be a better form of construction from the fatigue point of view, although there was some difficulty of reconciling the idea of large integral members with the concept of fail-safe. The Lockheed Electra was quoted as an example of a compromise in this dilemma. The wing had been designed with panels restricted to 20 inch width in order, so it was said, to ensure fail-safe conditions. There was some scepticism of this and it was suggested that it was the machining

problem, and not the requirements of fail-safe, which had dictated this restriction on the panel widths. It was now becoming apparent that the general concept of redundancy did not automatically coincide with that of fail-safe structure and at least one speaker was of the opinion that the more theoretically perfect type of construction, as represented by integral panels, would effectively reduce the strengths available subsequent to partial failure. This doubt was crystallised by the question of whether or not a crack, starting at some point in an integral panel, would stop at an integral stiffener. An indication of the probable answer was given by tests on sheets carrying stiffeners, some of which were held together by rivets and others which were bonded. It had been found that the bonded stiffeners were more effective in stopping crack propagation than the riveted stiffeners. The high energy required to make a crack cross an integral stiffener was given as the reason why, from the fail-safe aspect, the integral form of construction could be regarded as effectively composed of a number of discreet elements.

4.4. MATERIALS

The influence of the use of new alloys of the zinc bearing type on the fatigue life of aircraft was discussed. Queries were raised as to whether or not the use of older alloys in transport aircraft, although leading to a greater all-up weight, might not be a more economical proposition from the airline point of view than lighter aircraft employing the new alloys, with their higher cost and allegedly poorer fatigue qualities, on tension surfaces.

The general feeling was that a reversion to the older type of alloy would be tragic. In particular it was pointed out that laboratory fatigue tests indicated little difference between the basic fatigue properties of the materials but that the inclusion of notches and stress raisers, which were bound to occur in actual design, did in fact throw up a difference. It was also suggested that cracks propagated more easily in the newer alloys. Accordingly, the solution was very much in the hands of the designer to ensure that his detailed design was very good.

There was a general feeling that care and caution in the use of materials to D.T.D. specifications 363, 683 and 687 types were essential to the design of aircraft structures which were to be satisfactory from the fatigue point of view, but that the achievement of fatigue proof structures did not necessitate a reversion to the use of low strength materials.

4.5. SAFETY FACTORS FOR FATIGUE

In official requirements strength factors of up to three on some components were quoted to cover fatigue conditions. There was some question as to whether or not these could be removed and a more realistic approach be made by quoting factors on life rather than on a stress basis. It was pointed out that very high factors on life had been achieved during the testing of components which had been designed under current regulations employing static factors. However, such a result depended upon which part of the curve of stress *versus* life was being worked on during the test; if the flat part of the curve were being used then a very small change in a safety factor, based on stress, caused a tremendous difference in terms of life. Whatever safety factor was to be employed could only be made realistic by relating it in some way to the shape of that part of the curve appropriate to the actual loading conditions encountered.

5. Aircraft Inspectability

The considerable discussion which had taken place on the concept of fail-safe gave rise to some most interesting discussion on aircraft inspection. The fail-safe type of construction, which relied upon patching or replacement of cracked members, would in turn rely for its effectiveness on the ability to detect cracks by inspection during the operational life of the aircraft. One pre-requisite which the inspection staffs would demand was that the designer should indicate the probable regions in which cracks would appear and advise the operator as to how to detect the cracks. For exposed surfaces dye penetrant methods could be used and radiography could be used in other cases. It was noted that the Douglas and Convair companies were preparing complete X-ray schedules for their aircraft. These schedules indicated probable areas of cracking and gave details for siting of the X-ray film, the exposures to be used and the interpretation of the photograph. There was a general feeling of doubt of the infallibility of radiographical methods for this purpose and many thought that future designs should still provide good accessibility for visual inspection even up to the point that every major load-carrying element of the structure should be made visible. A number of discontinuities had to be expected in aircraft structures for access to pumps, tanks, etc., and it seemed possible that inspection doors could be provided for at least the most critical components.

Some further points on aspects of crack detection are given in the written contribution by Mr. J. F. Cuss, at the end of this report.

6. Operational Damage

Damage sustained during the operation of aircraft of a type not usually considered hazardous was pointed out as a potential danger. The scratches and dents, which for many years had been accepted as normal wear and tear, did not seem to be consistent with the careful design of the structure, particularly from fatigue considerations. Furthermore, several devices which were being suggested as a means to enhance fatigue life, such as taper pins and interference fits, were all particularly prone to damage in service. It was agreed that in this respect increasing reliance would have to be placed on the integrity of the man on the repair shop floor. There was, of course, scepticism of our continued ability to do this and although the benefits of using devices which relied upon this integrity were very great, it was felt that there ought to be some other line of defence. For example, engines relied upon the controlled tightening of joints, but one failure did not

cause a hazard. Again this seemed to indicate the wisdom of the fail-safe concept.

Whether or not one could rely upon no extra damage being done by careless maintenance, it was felt that some assessment of the more common partial damage of scratching should be made. In particular such damage might be simulated during fatigue tests; this did not seem to be a very difficult exercise to perform and might produce some useful information.

7. Design Methods

7.1. THE PHILOSOPHY OF SAFETY FACTORS

There had been much talk during the day on the newer concepts of aircraft design and it was with some surprise that many of the audience received the view put forward that the very old concept of safety factors was a bad philosophy. For all the care that was taken in assessing loads and in the use of theory in the design stage it was maintained that the present methods of use of safety factors reduced them to factors of ignorance and that they were, therefore, misleading. When a failure occurred the reason was not likely to be that the safety factors were too low but that the assumptions made at the design stage were not correct, or that the tolerances allowed on material variation were not correct. It was suggested that a better approach would be to take more conservative assumptions at the design stage and disregard the safety factor concept altogether. In answer to this it was pointed out that safety factors were slowly but continually being reduced and that all factors might eventually be put on a more realistic basis as we advanced in knowledge toward the more accurate estimation of loads and stresses, thus leaving a lower factor of ignorance.

7.2. INTERPRETATION OF THE ULTIMATE FACTOR

The logic of applying an ultimate safety factor of 1·5 was questioned in view of the change in loading distribution which could come about as a consequence of high structural deformations. It was suggested that the use of an ultimate factor somewhat lower than 1·5, say 1·2, with a criterion of "failure" based on deformation, might be more realistic. However, the full implications of such an approach could not be fully appreciated until this technique had been thoroughly tried on an actual aircraft.

7.3. STRESS ANALYSIS AND TESTING

It was felt that perhaps too much credence was placed on the mathematical approach of stress analysis, particularly in view of the fact that the safety factors employed were not consistent with the precision to which this analysis was carried out. "Stressing" should be based more on an intuitive engineering approach with mathematical investigation of structural efficiency to show only those types of structure which should be employed. Whether or not "stressing" was an exact science was not decided, but figures quoted to the effect that one out of every two designs proved to be under strength on test seemed to indicate that stressing was having some effect on the attempt to keep down structural weight.

Tests and testing methods also came in for some examination, and the increasing difficulties of reproducing actual loading conditions were brought to light. The case where both mechanical loads and heating had to be applied to some pre-determined distribution simultaneously was quoted as an example. Fatigue tests in which failures were repaired and the test subsequently continued were challenged as being unrepresentative; although one might presume that such tests would be representative of the operation life of a fail-safe structure if the failures repaired were not catastrophic.

There seemed to be fair agreement that proof tests were not generally as satisfactory as ultimate tests, since instability failures could occur very shortly after the proof load had been reached. As the number of ultimate tests which could be made was strictly limited there seemed to be a good case for making a number of tests at, say, 85 per cent. of ultimate.

A valuable aspect of the discussion was to suggest several topics which require treatment on their own. These have, of course, been noted and we may look forward to hearing more of them in future Section Lectures and Discussions organised by the Society.

J. F. CUSS (Chief Stressman, Gloster Aircraft Co. Ltd., *Associate Fellow*) *contributed*: Mr. Giddings dealt with fatigue matters from the standpoint of known loading conditions by gusts and maneouvres, but there was quite an important aspect of this problem which related to those items in an airframe and its associated parts, which were found to have some vibration which was liable to lead to fatigue; these were probably only discovered after tests in flight had been undertaken. It had been found, for example, that a fin of a certain aircraft vibrated at its natural frequency in flight to a fair amplitude and that, to a smaller amplitude, this was a fairly continuous state of affairs. It had been decided therefore, as a precaution, to undertake a fatigue test on a component of this aircraft on the ground. It had further been decided to make this a vibration fatigue test at its natural frequency, and this was one point where Dr. Walker's proposals for substituting mechanical means of loading fatigue specimens rather than for vibration at natural frequency, would not be appropriate.

Another point in this connection was probably of some interest; one speaker mentioned difficulty in determining when internal cracks in a structure had occurred, and in this connection his firm proposed, on their fatigue tests, to endeavour to ascertain the fact of a substantial cracking having taken place, by a change in the fundamental frequency of the fin component which was undergoing test. Both the internal frequency and the stiffness of the fin would be checked at intervals during the fatigue test run.

The Presentation of Fatigue Data for Fatigue Life Calculations

by

C. L. BORE, B.Sc.(Eng.), G.I.Mech.E., (Grad.R.Ae.S.)

(*Hawker Aircraft Ltd.*)

SUMMARY: A simple and convenient "endurance chart" for the presentation of basic fatigue data is described, where static failure is regarded as simply fatigue failure in one cycle of loading.

This chart shows the effects of mean stress, residual stress and pre-tension, and displays several interesting features of fatigue data. It is easily constructed directly from fatigue test results, and is very well suited to the calculation of stress concentration effects, including "plastic relief" effects.

With the aid of such charts the relative fatigue strengths and structural efficiencies of different materials may be readily compared, and it is clearly shown that in certain circumstances a "high-strength" alloy may in fact have considerably less fatigue strength than a "medium-strength" alloy at a given life, or conversely a lower life at a given stress level.

It is demonstrated that the fatigue life of a component subjected to combined mean stress and alternating stress may be found only with a knowledge of the complete fatigue characteristics of the material (such as are presented in the endurance chart); and that attempts to estimate fatigue life from spot-value comparisons, such as the fatigue strength at an arbitrary given endurance, can be dangerously inaccurate. A chart of the form described thus forms a valuable step towards the accurate calculation of fatigue life.

The method is illustrated by the provision of endurance charts for 14S-T (L.65), 75S-T, and D.T.D.683; and with experimental results for notched components of L.65 and D.T.D.683.

An example illustrates the application of the chart to the calculation of the fatigue life for the case of two independent systems of loading acting on a pressure cabin with circular window cut-outs.

Introduction

During a theoretical investigation aimed at finding consistent methods for the calculation of the fatigue life of any component under any system of fatigue loading, it was concluded that the life of a notched component could be related to the fatigue strength of the basic polished material, and that a very convenient method of presenting fatigue data for this purpose was in the form of the "endurance chart" to be described.

The scope of the present paper is restricted to a discussion of the merits of the endurance chart, the methods of fatigue life calculation facilitated by the chart, and the features disclosed by its use. For the sake of conciseness, a detailed consideration of the closely related phenomena of "scale effect" and "notch sensitivity" is excluded, although it is shown how these phenomena affect the fatigue-life calculations.

Notation

A	cross-sectional area at critical section (in.^{2})
f	stress (lb./in.^{2})
K	stress concentration factor at general point
N	endurance, number of cycles to failure
P	load on component (lb.)
R	"range ratio" $= \dfrac{\beta-1}{\beta+1}$
S	semi-range of alternating stress $= f_a$ (lb./in.^{2})
β	ratio mean stress: alternating stress; $\dfrac{f_m}{f_a}$.

SUFFICES

no suffix	general value
a	amplitude of alternating load or stress (Fig. 1)
i	intrinsic value
m	mean value (in time)
n	nominal value, calculated by simple (*e.g.* engineers') theory
p	peak value reached in each cycle
q	minimum value reached in each cycle
R	relative to polished-bar data
T	geometrical maximum value (*e.g.* that given by theory for isotropic material)

The principal notation adopted in this paper is illustrated in Fig. 1, where it can be seen that the quantity P_p denotes the peak load applied in each loading cycle, and f_p denotes the corresponding peak stress. The significance of the other loading suffices is shown diagrammatically.

The ratio of the mean stress f_m to the alternating stress f_a is denoted by β, which is hereafter called the "loading parameter," thus $\beta = f_m/f_a$. It may be remarked here that the "range ratio," R, widely used in the U.S.A. is defined by $R = f_q/f_p$, so that the range ratio is related simply to the loading parameter by:—

$$\beta = \frac{1+R}{1-R} \quad . \quad . \quad . \quad . \quad (1)$$

For fatigue loading by a single system of loads* in

*The case of a complex load system (*e.g.* such as occurs in a pressure cabin, where two or more independent sets of loads act concurrently) is considered later.

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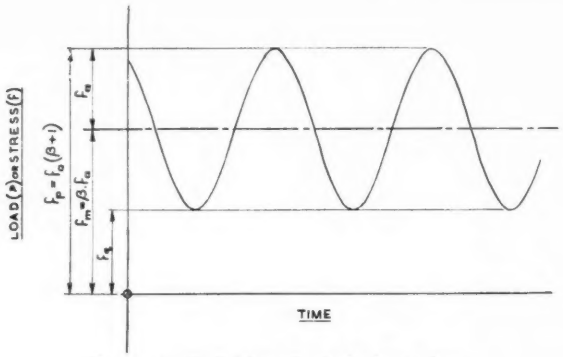

FIGURE 1. Definition of principal notation.

which the alternating load has constant amplitude, any possible combination of mean and alternating stresses can be defined by the two quantities f_p and β.

The physical significance of f_p is obvious, and the significance of the loading parameter can be seen from the following discussion. Consider, for example, a number of geometrically similar components mounted at different points in (say) an aircraft wing. If the stresses everywhere in the wing are proportional to the applied load, it is evident that, although the magnitude of the loads and stresses on individual components will differ from place to place, the ratio of mean load to alternating load for every component is constant and equal to the corresponding ratio for the applied loads. Thus, although the stress level f_p varies from component to component, the loading parameter β is a constant throughout the structure. That β=constant is a necessary condition for the valid comparison of fatigue strengths of similar or dissimilar components may be shown by means of a simple dimensional analysis in which the strength is considered as a function of f_a, f_m, A and N; where A is the cross-sectional area at the critical section. This demonstration will be left to the reader.

It will be noted that two frequently used test loadings are simply defined by the loading parameter; "fully reversed loading" corresponding with $\beta=0$, and "repeated loading" with the minimum stress zero corresponding with $\beta=1$. If the loading parameter is used to define test conditions, the use of the two phrases quoted becomes unnecessary.

It is felt that the loading parameter β is preferable to the range ratio R because the sign of β is equal to the sign of the mean stress, and the numerical values of β change by convenient increments for conveniently spaced endurance curves.

In an aircraft structure the loading parameter, or its equivalent, is dictated by the manoeuvres to which the aircraft is subjected, and for a given type of duty it may be considered that β is a constant for any aircraft performing that duty (subject to corrections taking account of the aerodynamic characteristics of the aircraft). Since much of the available information on the fatigue of actual components lies in the knowledge that in service, when made in a particular material the component had a satisfactory life (or otherwise), emphasis will be placed in the following discussions on comparisons in which the *change of fatigue life* is estimated for geometrically similar components made from different materials; the service *loading* conditions

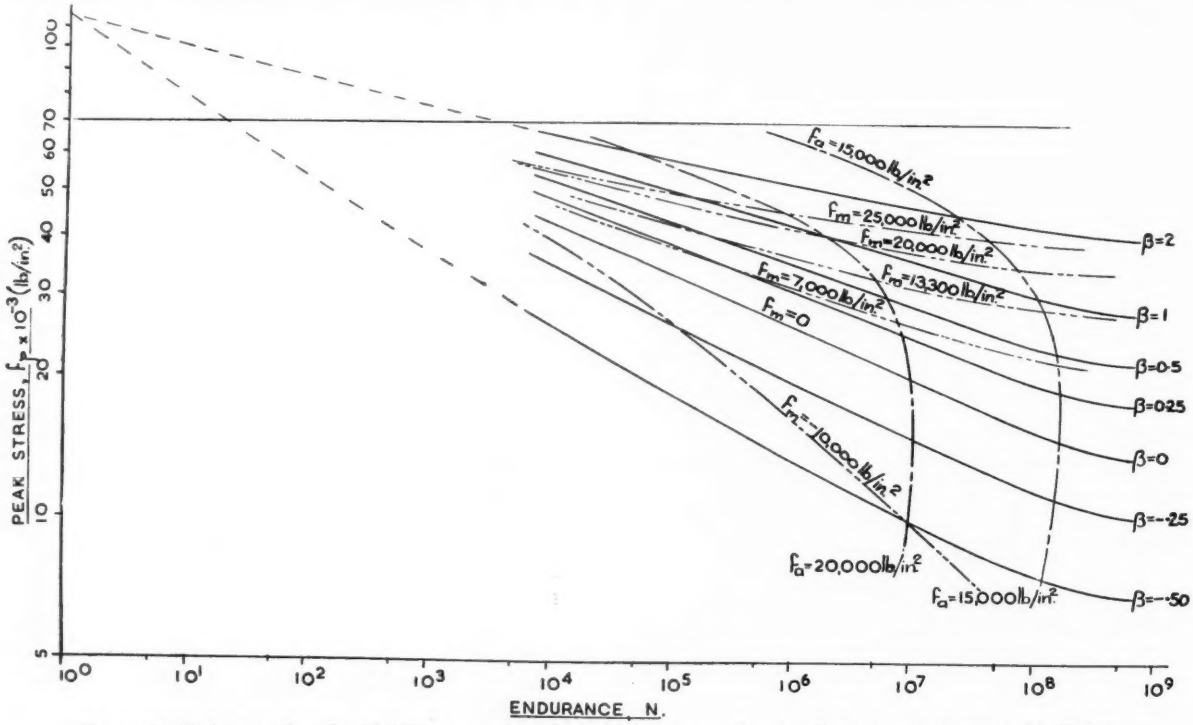

FIGURE 2. Endurance chart for 14 S-T bar material. Deduced from comprehensive direct-stress tests reported in Ref. 6.

remaining constant, although the overall scale of the component will be considered as under the control of the designer.

The Basic Diagram

Figure 2 shows a typical "endurance chart" for direct-stress polished bar specimens, which in this case applies for 14S-T (practically L.65). It will be noted that both the stress (f_p) and endurance (N) axes are logarithmically divided, and that the endurance axis is much extended in comparison with most conventional S-N diagrams.

The basic information is presented as a grid of curves drawn for various constant β, where any individual curve of f_p against N for constant β will be called an endurance curve.

Figure 2, for example, was constructed by carefully cross-plotting from the extensive tabulated data of Ref. 6, which may be converted to the parameters of the present paper and plotted as shown in Fig. 3.

It should be noted that each marked point in Fig. 3 represents the faired experimental results for a number of specimens, so that the final endurance curves represent the mean results for a very large programme of fatigue tests.

Most of the remaining endurance curves presented in the course of this paper (*e.g.* Figs. 4 and 5) were derived by means of basically similar processes of cross-plotting, using experimental data from such sources as Refs. 7 and 8.

Upon examination of the endurance charts thus constructed, some features which greatly facilitate the construction of similar charts from meagre data may be seen. Thus, the extrapolated endurance curves all appear to tend to a focus on the $N=1$ cycle axis, at a point which might be termed the intrinsic tensile strength; and it is evident that for much of their length these endurance curves are practically straight.

It is well known that the $\beta=0$ endurance curve for polished-bar specimens of many structural metals, (*e.g.* steels, aluminium, brass, many aluminium alloys, etc.) is straight for most of its length, when plotted on double logarithmic axes (*see* for example Refs. 9 and 10), so that, since the proposed method of plotting results in sets of endurance curves with a distinct family resemblance, each curve tends to be practically straight over a considerable part of its length, as exemplified in the diagrams Fig. 2, 4, 5, etc.; while the extension of the endurance curves to low endurances naturally tends to increase the length of the straight portions.

When considerable scatter of experimental results exists, the knowledge that the mean line through the points should be straight (or nearly so) is of considerable help in drawing reasonably accurate curves to represent the data, and also allows the simple use of a "least squares" method.

The marked family resemblance between the individual endurance curves also simplifies the problem of drawing the chart.

A point of interest shown by the endurance curves of Fig. 2 is the tendency to flatten out near an endurance of 10^9 cycles, which points to the possibility that a definite endurance limit may exist for aluminium alloys, albeit at endurances greater than any achieved in current practical testing. *It will be seen shortly that this tendency exists also for other aluminium alloys.*

The basic grid of endurances curves so far described contains all the information necessary for the derivation of the additional curves shown on Fig. 2, and *almost* all the information needed for elementary fatigue life calculations.

Additional Curves

The variation of fatigue strength with endurance for the condition of constant mean stress is shown by chain dotted curves on Fig. 2, together with the $\beta=0$

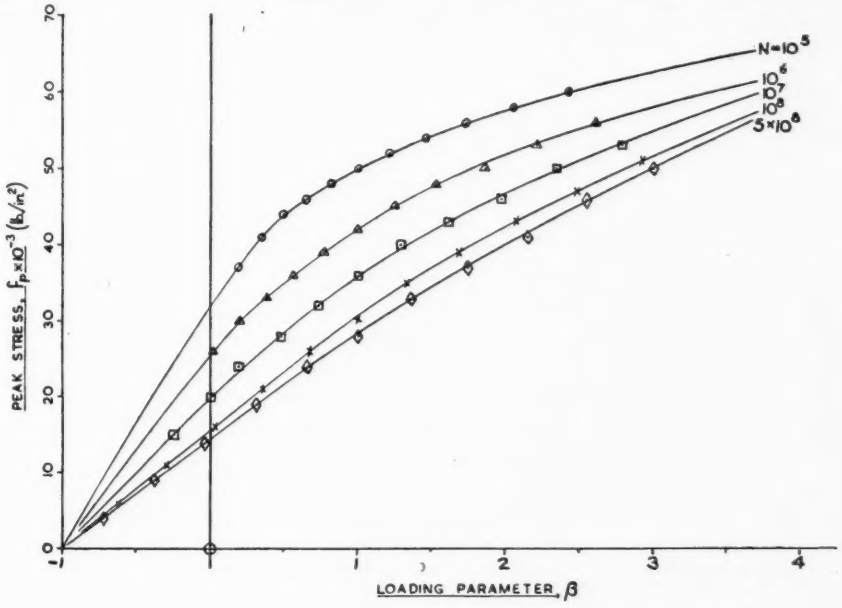

FIGURE 3. Experimental data of Ref. 6 plotted in form suitable for cross-plotting to endurance chart (Fig. 2).

endurance curve, (which has a constant mean stress of zero). These curves all appear to emanate from the intrinsic tensile strength point and diverge on either side of the $\beta=0$ curve. Except for the zero mean stress curve, the loading parameter always varies with the endurance when a component is tested under constant mean stress, and it will be shown later that this variation of loading parameter with endurance becomes very marked in a notched component.

Two curves are shown on Fig. 2 which give the variation of fatigue strength with endurance for the condition of constant alternating stress. These clearly show that the endurance (of a polished bar specimen), under constant alternating stress, decreases as the mean stress departs from zero, slowly at first, *but rapidly at high mean stress.*

This decrease of endurance depends on the magnitude of the alternating stress and working from Fig. 2, it is found that the endurance decreases by a factor of four as the mean stress goes from zero to 25,000 lb./in.^{2} when the alternating stress is 15,000 lb./in.^{2}, but by a factor of ten when the alternating stress is 20,000 lb./in.^{2}.

Now the *mean* stress can be controlled to some extent in parts of some components by methods which introduce surface residual stresses (such as shot peening, surface cold rolling, and nitriding), so that for these parts the maximum endurance will be obtained when the mean stress due to the combined residual stress and mean loading is near zero. Thus a residual compressive stress is most effective when it is equal in magnitude to the tensile mean stress due to the extraneous mean loading.

The case of the prescribed constant maximum stress is particularly simple. This case, which is applicable to a bolt subjected to tensile loading with variable pre-tension, is represented by a horizontal line on the chart. From this, it is clear that as β increases the endurance increases very rapidly. As an illustration of this point, consider a member subjected periodically to tensile loads giving rise to maximum stresses of 38,000 lb./in.^{2} If the minimum value of the load is zero, then the lowest possible value of β is equal to unity, which gives an endurance of 4×10^6 cycles. Now the minimum stress in each loading cycle is the pre-tension stress, which corresponds to f_q in Fig. 1, and this may be expressed in terms of β, thus:—

$$f_q=f_p\frac{\beta-1}{\beta+1} \quad . \quad . \quad . \quad . \quad (2)$$

Hence the pre-tension necessary to make $\beta=2$ with $f_p=38{,}000$ lb./in.^{2} is 38,000/3, or 12,670 lb./in.^{2} approximately; and if the endurance curves for L.65 really do flatten out near 10^9 cycles endurance, this loading will ensure infinite life. The interesting point to note here is that for any material with a definite endurance limit *an infinite endurance can be achieved by pre-tension to a quite modest fraction of the peak load; e.g.* in the example quoted, just one third. What is more, this pre-tension can be found very simply by reading from the endurance chart the value of β for that endurance curve which just keeps wholly above the peak stress ordinate prescribed.

Comparison of Different Materials

The fatigue strengths of two different materials under all possible fatigue loadings may be compared with ease by drawing the two grids of endurance curves on a single pair of graph axes, as shown in Fig. 4, where the locus of the intersection points for curves of equal β is drawn as a dotted line.

Comparing the relative positions of the respective endurance curves it can be seen that to one side of this dotted line (the " merit boundary ") one material is always the stronger under fatigue loading, while on the other side the situation is reversed.

The fact that such a boundary exists is interesting, for the two materials compared in Fig. 4 are 14S-T and 75S-T bar materials, which are known as " medium strength " and " high strength " alloys respectively. It is therefore worthy of note that, for conditions above the

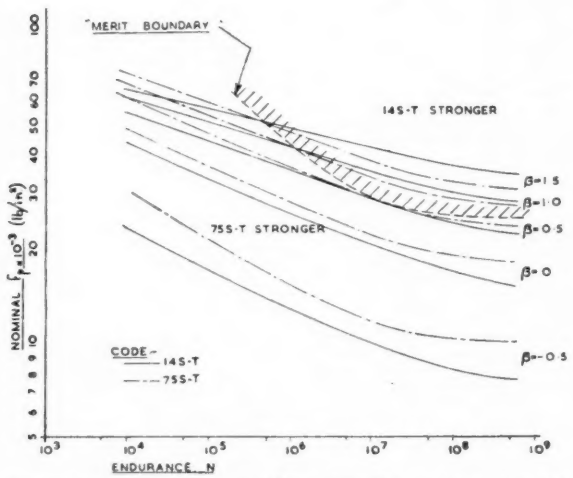

FIGURE 4. Comparison of fatigue strengths of 14 S-T (L.65) and 75 S-T. Deduced from Refs. 6 and 7.

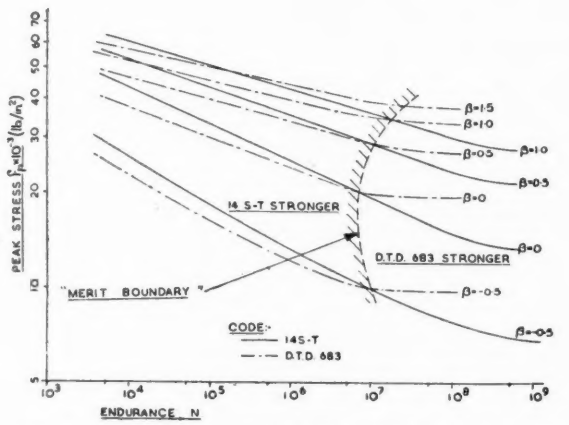

FIGURE 5. Comparison of fatigue strengths of 14 S-T and D.T.D.683. Deduced from Refs. 6 and 8.

merit boundary on Fig. 4, the medium strength alloy has greater fatigue strength than the high strength alloy.

Now in fatigue calculations, even more than in many other fields, it is unwise to generalise from the particular, as may be seen by referring to Fig. 5. This figure compares 14S-T with another high strength alloy, where it can be seen that not only is the merit boundary of a different shape from that in Fig. 4, but the respective merits of the two materials are almost entirely the reverse of the previous case, with the D.T.D. 683 now winning at long endurance. Incidentally, the pronounced flattening of the D.T.D. 683 endurance curves at high endurance is notable in this figure.

Such a comparison is particularly useful when a part has to be designed to have a given endurance, for the service loading dictates the effective value of β, and the comparison then shows directly which of the materials compared is the stronger for the particular application.

This type of comparison may be extended to more than two materials, and also to the comparison of structural efficiencies; for if the stress ordinates are divided by the material densities, the resultant ordinates represent service strength per unit weight.

This division of stress ordinates is very simple since the stress axis is logarithmically divided, and the multiplication or division of every ordinate on a curve may therefore be accomplished by merely moving the curve bodily upwards, or downwards, as the case may be. In practice, if the relative efficiencies of two materials were to be compared whose respective densities were in the ratio of (say) 1:1·2, it would merely be necessary to move the grid of the curves for the second material bodily down the chart until any stress ordinate was 1/1·2 (=0·833) of its original value.

Calculations Based on Inadequate Data

The comparisons of material presented in Figs. 4 and 5 show that one material may be stronger than another material at given endurance, yet weaker at another endurance; and that a similar situation can exist also for different loading parameters at given endurance.

It is instructive to consider the component lives which result if certain inadequate fatigue calculations were the basis of design. To fix ideas, alternative designs of component, to be made from 75 S-T material, will be considered as proposed replacements for a part made from 14 S-T.

The specified lives and working maximum stresses are not necessarily representative of service conditions, but are chosen more or less arbitrarily to show that *inadequate fatigue calculations may lead to dangerously inadequate designs.*

For the purpose of illustrating the principles, it will be assumed for the time being that the fatigue life of a component is dependent only on the maximum stress for any point within the component, the loading parameter and the endurance. It is further assumed that the maximum stress is always proportional to the applied load.

The discussion of these assumptions is deferred to a later stage in this paper, where it is shown that both assumptions are practically valid over a considerable range of conditions, although certain reservations have to be made.

In each of the simple examples which follow it is supposed that the original design of component has just sufficient fatigue life to survive the required length of time under service loading.

1. COMPARISONS ON BASIS OF ARBITRARY LOADING PARAMETER, $\beta=0$

Suppose that a 75 S-T replacement for a 14 S-T part is required in which the 14 S-T component survives 10^7 cycles of loading. The information supplied is that under "completely reversed loading" ($\beta=0$), *at* 10^7 *cycles endurance,* the fatigue strength of 75 S-T is 22,000 lb./in.², compared with 20,500 lb./in.² for 14 S-T (*see* Fig. 4).

Working on this basis, the working stresses on the new part are allowed to reach 22·0/20·5 times the stresses allowed in the old part.

Now suppose that the actual service loading is equivalent to $\beta=0{\cdot}5$; then to sustain 10^7 cycles the old part must have been stressed to a maximum of 28,700 lb./in.² (Fig. 4). The stresses in the replacements will therefore be $(22{\cdot}0/20{\cdot}5)\times 28{,}700 = 30{,}800$ lb./in.² and with $\beta=0{\cdot}5$ this results in a life of 5×10^6 cycles of the service loading.

Thus, in this example, the life of the replacement part turns out to be only half that of the original design; *even though the calculation was made on a basis of "fatigue strength" at the correct endurance.* The source of the error here is neglect to use fatigue strengths compared for the correct *loading parameter* as well as endurance. It is obvious that using an incorrect endurance as well as incorrect loading parameter could lead to larger errors.

2. COMPARISON ON BASIS OF STATIC ULTIMATE STRENGTH

For this example it will be supposed again that the original component is satisfactory in service for 10^7 cycles at a service loading of $\beta=0{\cdot}5$.

The information supplied in this case states that the ultimate tensile strength of 75 S-T is about 32 T/in.², compared with 28 T/in.² for 14 S-T.

On this basis the 75 S-T component would be stressed to 32/28 times the level used on the original part, resulting in a working stress of 32,000 lb./in.² This (from Fig. 4) results in a life of some $2{\cdot}6\times10^6$ cycles in the replacement part: only a quarter of the original life.

Clearly this basis of calculation is quite inadequate, despite the widespread use of this method as the basis of design for aircraft structures.

3. COMPARISON ON BASIS OF EQUAL STRESS

Even if the high-strength material is worked at only the same stress as the 14 S-T component, it is still possible to produce an unsafe design.

Consider now a 14 S-T component which is satisfactory at an endurance of 10^7 cycles under a service loading $\beta=1$. The peak stress is therefore 35,000 lb./in.^{2}; but this stress level at $\beta=1$ on a 75 S-T component results in an endurance of $6{\cdot}5\times10^6$ cycles, or only 65 per cent. of the life of the original part.

Conclusions on Inadequate Fatigue Calculations

Each of these examples serves to illustrate the fact that satisfactory service lives for components may be achieved safely and surely only by means of adequate fatigue considerations, which must take into account both the required life and the correct loading parameter.

High strength alloys are *not necessarily* stronger under fatigue (*i.e.* service) loads, and attempts to take advantage of high static tensile strength may lead to extremely unsafe designs.

It can be seen that if it is desired to design the most efficient possible structure to last a given time, then the most direct way to ensure this is to select the most efficient material *for the given endurance and loading parameter* by means of merit diagrams of the type suggested above, and load it to the correct peak stress for the given endurance.

The two materials compared were chosen quite arbitrarily merely because the detailed data required for the construction of the endurance charts was available, and it is very probable that other pairs of material would give even more startling changes in endurance.

It is clear that large changes in component life can result from apparently innocuous changes of material or stress level, and that estimates based on incomplete data are completely unreliable.

Stress Concentration

The examples given assume implicitly that the maximum peak stresses reached in the components considered were proportional to the applied stresses, but since the examples were proposed by means of comparisons of parts supposed to be geometrically similar, no knowledge of the actual stress concentration effects in the component was necessary. It is now desirable to consider the methods by means of which the life of a component with a known stress concentration factor may be found.

Consider first an elastic component having a notch which, in the vicinity of the notch, multiplies the nominal stresses applied to the component by the factor K_T. Then if the *nominal* applied stress is defined by (f_{pn}, β), the *maximum* stress at the root of the notch will be defined by $(K_T \,.\, f_{pn}, \beta)$.

That this is so is easy to see, for the maximum stress in the component at any instant of time will be K_T times the nominal stress at that instant, so that every stress is multiplied by the same factor, leaving β constant.

If the stress axis on the endurance chart is regarded as the scale of *nominal* peak stress, and if endurance curves are already available for polished-bar specimens in which no stress concentration exists, then the nominal endurance curves for these notched components will be simply the polished-bar curves moved bodily down the stress axis to $1/K_T$ times the original ordinates.

Now scale effects complicate this aspect of fatigue somewhat, but a rather over-simplified consideration will suffice here to introduce the "relative" stress concentration factor K_R.

Suppose that our experimental polished-bar fatigue specimens have in them small but unavoidable stress raisers, then the endurance curves for these specimens would fall some way below those applicable to hypothetically perfect specimens, exactly as described above for the "notched component." Now these experimental polished-bar stresses are the best data available for calculations, so that it is necessary to express the stress concentration factors for known notches in terms of these experimental stresses. The ratio of the *nominal* fatigue stresses at failure for the experimental polished-bar specimens and the notched components respectively is then called the "relative stress concentration factor, K_R". As this argument might imply, this factor K_R is usually (although not necessarily) less than the full theoretical stress concentration factor (K_T) for a homogeneous material.

Thus, when relating the fatigue stresses in notched components to those in polished-bar specimens it is the *relative* stress concentration factor which is of practical significance; so that the endurance curves for a notched component with (say) $K_R=4$ will be moved bodily down the stress axis from the polished-bar ordinates to one quarter of the polished-bar stresses, as shown in Fig. 6. Note that this operation is made possible by the logarithmic division of the stress axis.

It will be shown shortly that experimental results accord with this simple method for all β at sufficiently large endurances. When the maximum stresses in the component become sufficiently large, however, the relative stress concentration factor starts to change; decreasing with increasing maximum stress from a value close to K_T, towards unity.

Since the stresses now plotted on the endurance chart are *nominal* stresses, it is convenient to regard the point on each endurance curve where this change starts as a function of endurance and β, rather than effective maximum stress and β. Now the locus of the points on the endurance curves at which this change of stress concentration factor starts, which will be called the relief boundary, appears to differ from material to material; but it seems likely that the boundary remains constant for different notches in a given material. In other words it seems likely that the curve defining the relief boundary can be regarded as fixed to the *nominal* endurance curves, wherever they be moved, as shown in Fig. 6.

Below, and to the right of the relief boundary (Fig. 6), the effective concentration factor for the notched component relative to the polished-bar results is constant and equal to K_R.

Little direct data (*i.e.* data from tests with β constant) is available to show the detailed changes in effective stress concentration factor which occur above the relief

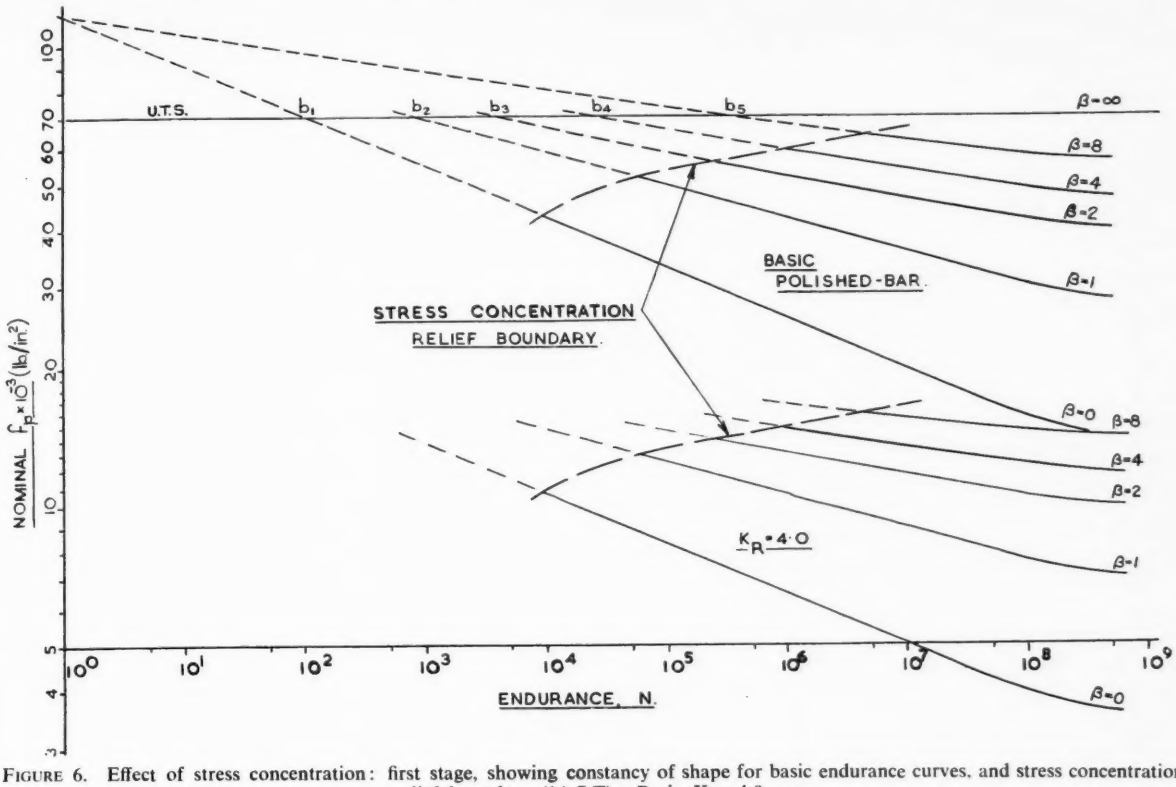

FIGURE 6. Effect of stress concentration: first stage, showing constancy of shape for basic endurance curves, and stress concentration relief boundary (14 S-T). Basic $K_R = 4{\cdot}0$.

boundary, but it will be shown next that a simple construction gives endurance curves which are completely in accord with some extensive fatigue tests performed with constant nominal mean stress.

Consider again Fig. 6, and note the horizontal line drawn at 70,000 lb./in.² stress, which is approximately the ultimate tensile strength for D.T.D. 364 extrusion. The extrapolated polished-bar endurance curves for 14 S-T material tested under direct stress intersect this horizontal line in a series of points b_1, b_2, and so on. Now assuming that 14 S-T is equivalent to D.T.D. 364, it can be said that if the effective stress concentration factor for a notched component is ever reduced to unity by plastic-flow effects, then it should be unity at the points b_1, b_2, etc.

In the absence of comprehensive test data giving a more accurate stress level, we take these points as the upper limit of stress-concentration relief, and join them to the corresponding points d_1, d_2, d_3, etc., on the relief boundary by straight lines (*see* Fig. 7).

The endurance curves *abcde* thus constructed appear in fact to be remarkably close to the curves which might be obtained in actual experiments, as will be shown next.

The endurance curves *abcde* of Fig. 7 were constructed for a notched component made from D.T.D. 364 extrusion, with $K_R = 4{\cdot}0$ (for the long-endurance end of the chart), assuming the relief boundary to be as sketched. To compare this grid with the available experimental results, these latter results are plotted directly on the chart, with the value of β actually used in the tests written beside each point. It will be noted that the experimental values of β are in good agreement with the derived endurance curves.

Now the experimental results were obtained in sets of tests with the mean stresses constant at 20,000 lb./in.², 13,300 lb./in.² and 7,000 lb./in.² respectively, so the next stage of the comparison is to derive *from the endurance curves* the curves of constant mean stress. This is quite simple, for by definition:—

$$f_p = f_m + f_a \quad . \quad . \quad . \quad . \quad (3)$$

and $$\beta = \frac{f_m}{f_a}$$

therefore $$f_p = f_m\left(1 + \frac{1}{\beta}\right), \quad . \quad . \quad (4)$$

so that the required curve of constant f_m may be constructed by selecting convenient values of β and finding the appropriate stress ordinates, over a range of β. The constant mean stress curves of Fig. 7 were derived in this way.

It will be noted that the experimental data agrees well with the derived constant-f_m curves, showing that the grid of endurance curves derived for the notched component is an accurate representation of the experimental facts.

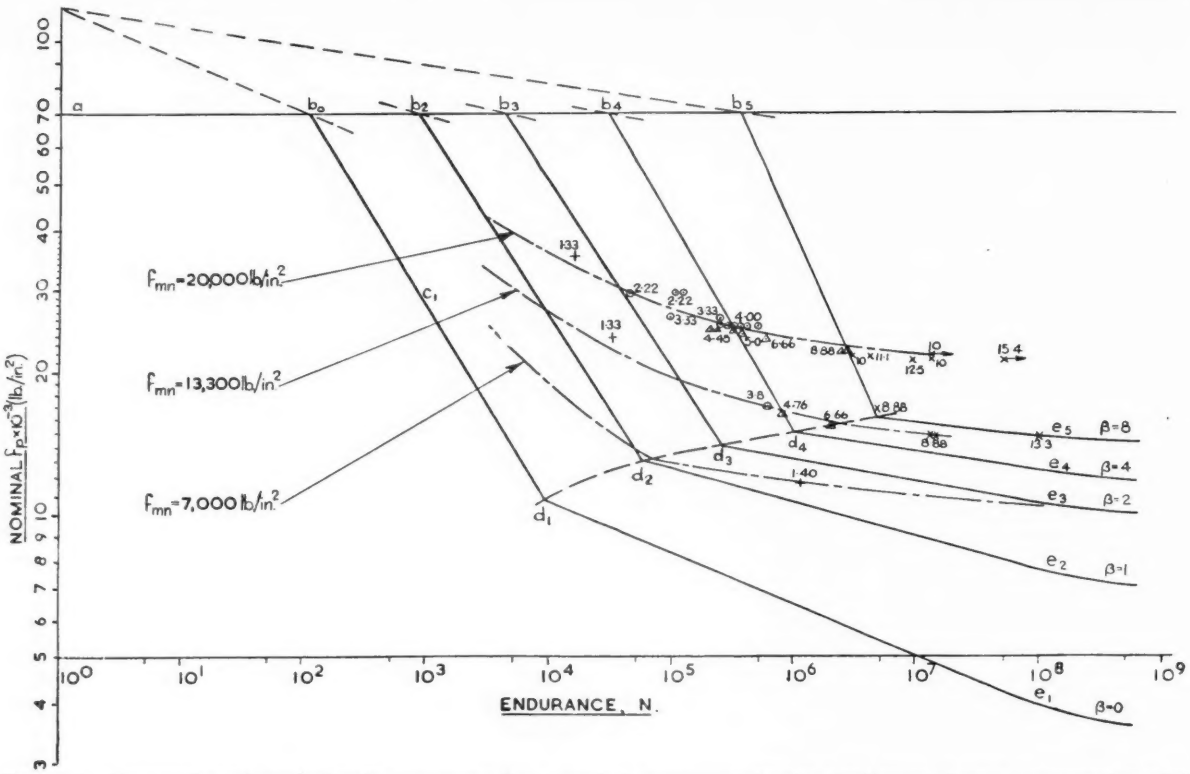

FIGURE 7. Construction of nominal endurance curves for a notched component, showing significance of stress concentration relief boundary, derived constant mean stress curves, and experimental data for comparison. Experimental points taken from Refs. 3, 4 and 5. Basic $K_R=4{\cdot}0$: Figures written by experimental points are experimental values of β.

This experimental check may also be made in another way, by replotting the derived constant-f_m curves of Fig. 7 in the form of ordinary *S-N* curves, to allow direct comparison with the original form of the experimental data. This comparison is shown in Fig. 8, where agreement is again evident.

Since it has now been shown that the derived endurance curves are in reasonable agreement with the experimental evidence, these curves will be taken as substantially correct for present purposes.

It is instructive to investigate the order of error in the calculated apparent "stress concentration factor" when the definition of this "factor" fails to take into account the fact that *the mean stress, as well as the alternating stress, is affected by the notch.*

In Table I the substantially correct value of the relative stress concentration factor (K_R) is listed for the notched component when loaded with the given nominal mean stress. Two erroneous values of "stress concentration factor" also are tabulated, together with the approximate errors involved.

The fallacious stress concentration factors listed are defined as follows:—

$$K_{F1}=\frac{f_{an}\text{ for notched component}}{f_{an}\text{ for polished bar (for }\beta=0)}\text{, at given endurance}$$

$$K_{F2}=\frac{f_{an}\text{ for polished bar at given }f_{mn}}{f_{an}\text{ for notched component at same }f_{mn}}\text{, at given endurance.}$$

Thus, K_{F1} compares the alternating stress, applied to the notched component for a given life, with the alternating stress which may be applied to a polished bar for failure at the same life ($\beta=0$); while K_{F2} compares the alternating stress applied to the notched component with given mean stress at a given life and the alternating stress which may be applied to a polished bar *in conjunction with the same nominal value of mean stress for the same life.*

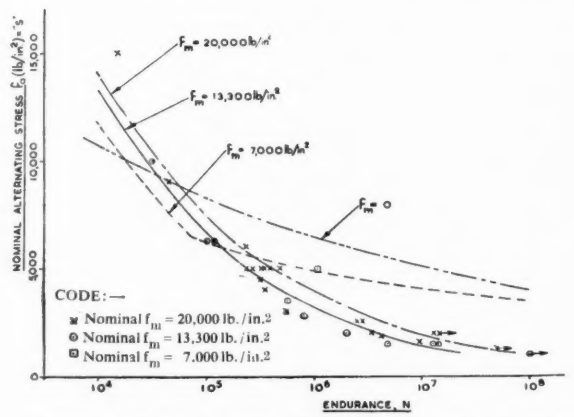
NOMINAL ALTERNATING STRESS f_a (lb./in.^{2}) × 5
ENDURANCE, N
f_m = 20,000 lb/in.^{2}
f_m = 13,300 lb/in.^{2}
f_m = 7,000 lb/in.^{2}
f_m = 0
CODE:—
Nominal f_m = 20,000 lb./in.^{2}
Nominal f_m = 13,300 lb./in.^{2}
Nominal f_m = 7,000 lb./in.^{2}

FIGURE 8. *S-N* curves for D.T.D.364 component with basic $K_R=4{\cdot}0$, derived from constructed endurance curves of Fig. 7. Experimental points taken from Refs. 3, 4 and 5.

TABLE I

COMPARISON OF ERRORS DUE TO NEGLECT OF LOADING PARAMETER

Basic $K_R = 4{\cdot}0$, D.T.D.364

f_{mn} (lb./in.²)	K, and error	Endurance N (cycles) 10^4	10^5	10^6	10^7	10^8
20,000	K_R	1·81	2·23	—	—	—
	K_{F1}	3·1	4·5	6·6	10·5	15·8
	$\frac{K_{F1}-K_R}{K_R} \times 100$	70	101	—	—	—
	K_{F2}	2·5	3·6	5·5	9·3	14·8
	$\frac{K_{F2}-K_R}{K_R} \times 100$	39	63	—	—	—
13,300	K_R	2·18	2·88	3·87	4·00	4·00
	K_{F1}	3·3	5·0	8·0	14·3	17·5
	$\frac{K_{F1}-K_R}{K_R} \times 100$	50	74	107	258	338
	K_{F2}	2·8	4·4	7·2	13·1	16·8
	$\frac{K_{F2}-K_R}{K_R} \times 100$	30	54	86	228	320
7,000	K_R	2·86	4·00	4·00	4·00	4·00
	K_{F1}	3·7	5·5	5·2	4·9	4·6
	$\frac{K_{F1}-K_R}{K_R} \times 100$	28	38	31	22	15
	K_{F2}	3·4	5·0	5·0	4·6	4·4
	$\frac{K_{F2}-K_R}{K_R} \times 100$	19	25	24	16	11
0	K_R	4·0	4·0	4·0	4·0	4·0
	K_{F1}	4·0	4·0	4·0	4·0	4·0
	$\frac{K_{F1}-K_R}{K_R} \times 100$	0	0	0	0	0
	K_{F2}	4·0	4·0	4·0	4·0	4·0
	$\frac{K_{F2}-K_R}{K_R} \times 100$	0	0	0	0	0

The values of f_{an} for the notched component derived from Fig. 7 are plotted on Fig. 8, while the values of f_{an} for polished bar direct-stress specimens were derived from Fig. 2, being plotted explicitly on Fig. 9.

Table I shows that while the fallacious stress concentration factors K_{F1} and K_{F2} give correct results at zero mean stress, large errors occur at high values of nominal mean stress; amounting to 338 per cent. and 320 per cent. respectively at 10^8 cycles endurance, with 13,300 lb./in.² mean stress.

It is therefore evident that neglect of the loading parameter (or an equivalent, such as the R value) leads to quite unacceptable errors. Thus, a constant value of relative stress concentration factor K_R can be expected from fatigue test results only when the polished-bar and notched-specimen are compared under conditions of given β as well as given endurance.

It might be noted here that results of a similar nature have been obtained from test results on cylindrical notched specimens of D.T.D. 683, shown on Figs. 10, 11 and 12.

This section has introduced the concept of the "stress concentration relief boundary" which, it is thought, is probably a solution to the problem of calculating the effects of stress relief in highly-stressed notched components. This boundary, then, is the extra bit of information hinted at in the course of the initial description of the endurance chart, which will allow the calculation of fatigue life given only the loading conditions, the elastic stress concentration in the component, and the fatigue data described.

Application of Chart to Components Loaded by Two Independent Load Systems

So far, the use of this endurance chart has been explained by reference to components which are assumed to be loaded effectively by a single system of loads; that is, a system in which all applied loads are in constant ratio to each other, and vary in synchronism.

This type of loading system is very common, embracing all components loaded at a single point as well as the more complicated structures, such as aircraft wings, in which for many practical purposes the stress everywhere in the wing can be assumed proportional to the total wing load, by virtue of the fact that the principal loads are distributed in constant proportions over the surface.

The investigation of a structure loaded in this way is simple because the loading parameter β is a constant

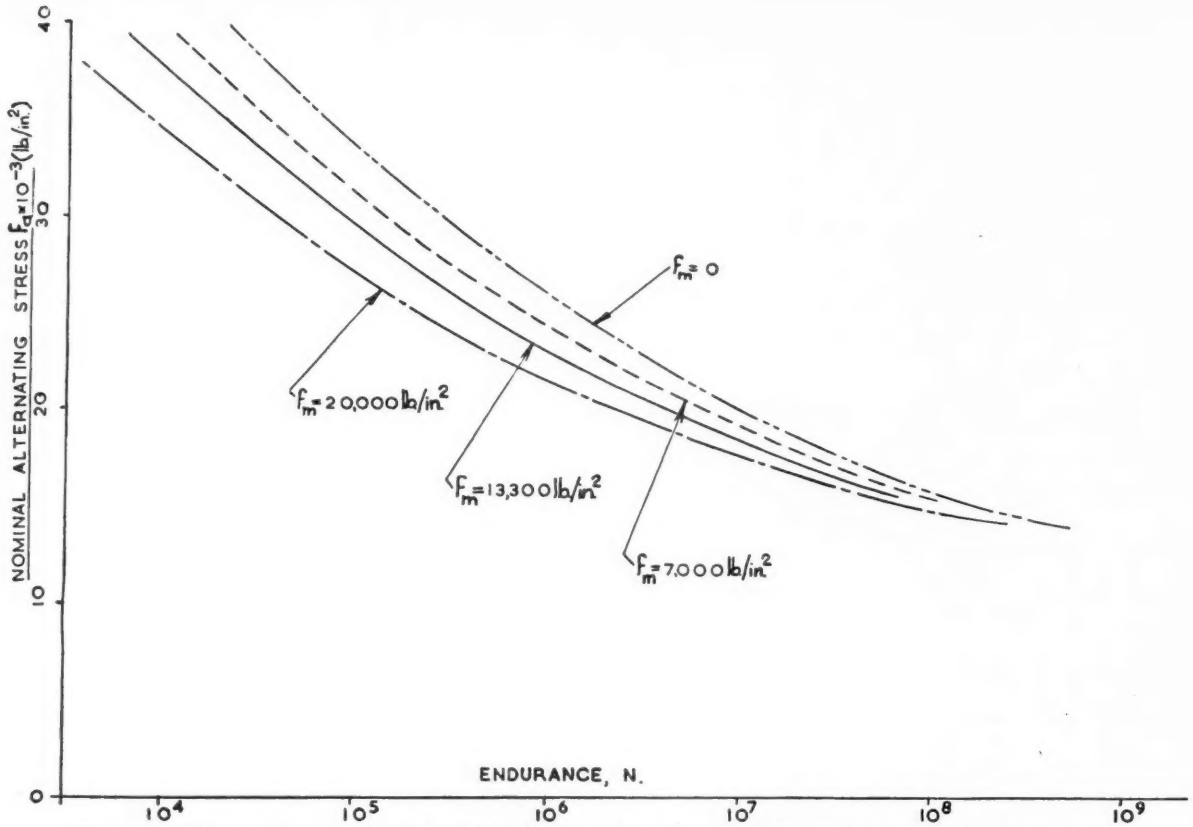

FIGURE 9. *S-N* curves for smooth, polished D.T.D.364 bar under various nominal mean stresses. Derived from Fig. 2.

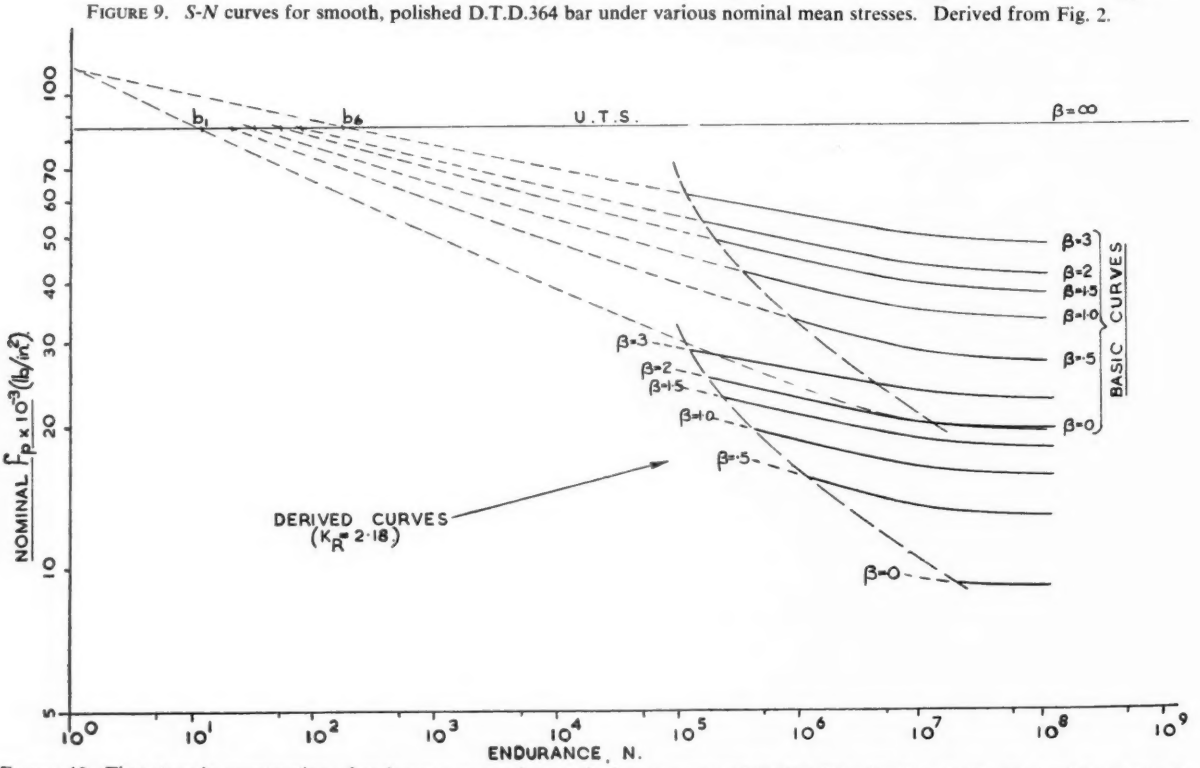

FIGURE 10. First stage in construction of endurance curves for notched component of D.T.D.683 with $K_R = 2{\cdot}18$. Derived from Fig. 5.

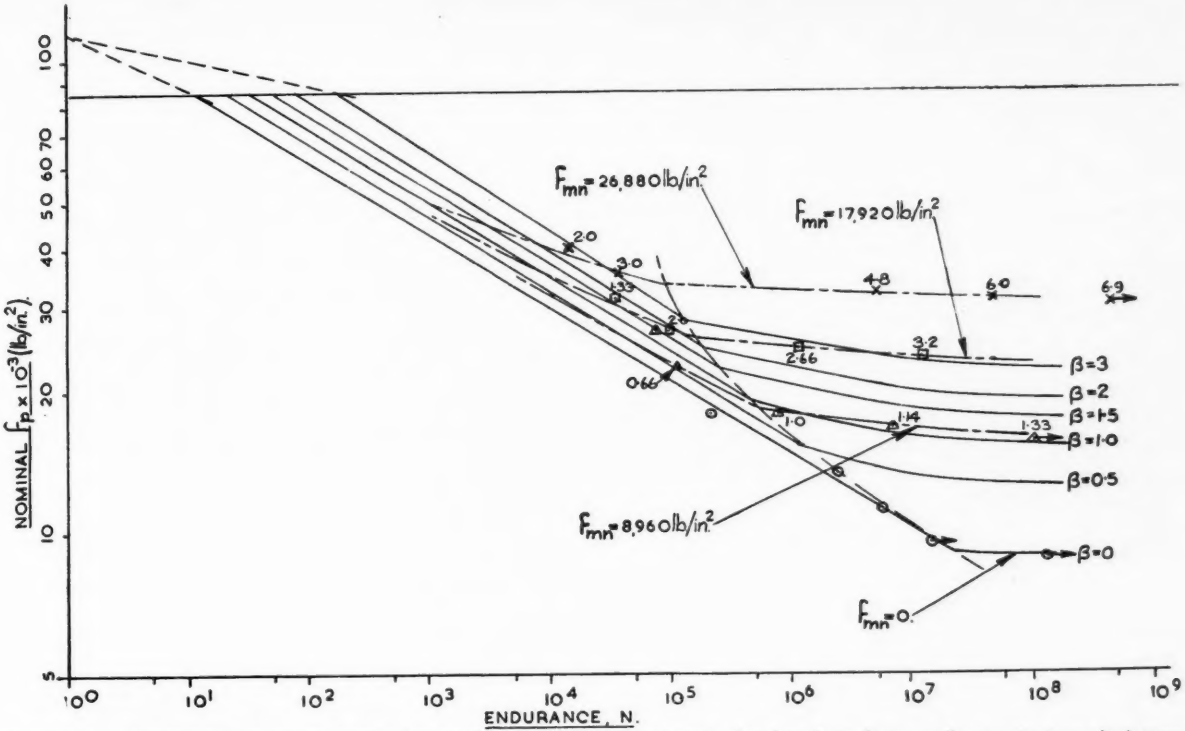

FIGURE 11. Constructed endurance curves for notched D.T.D.683 component, showing derived curves for constant nominal mean stresses. Experimental points from Ref. 8.

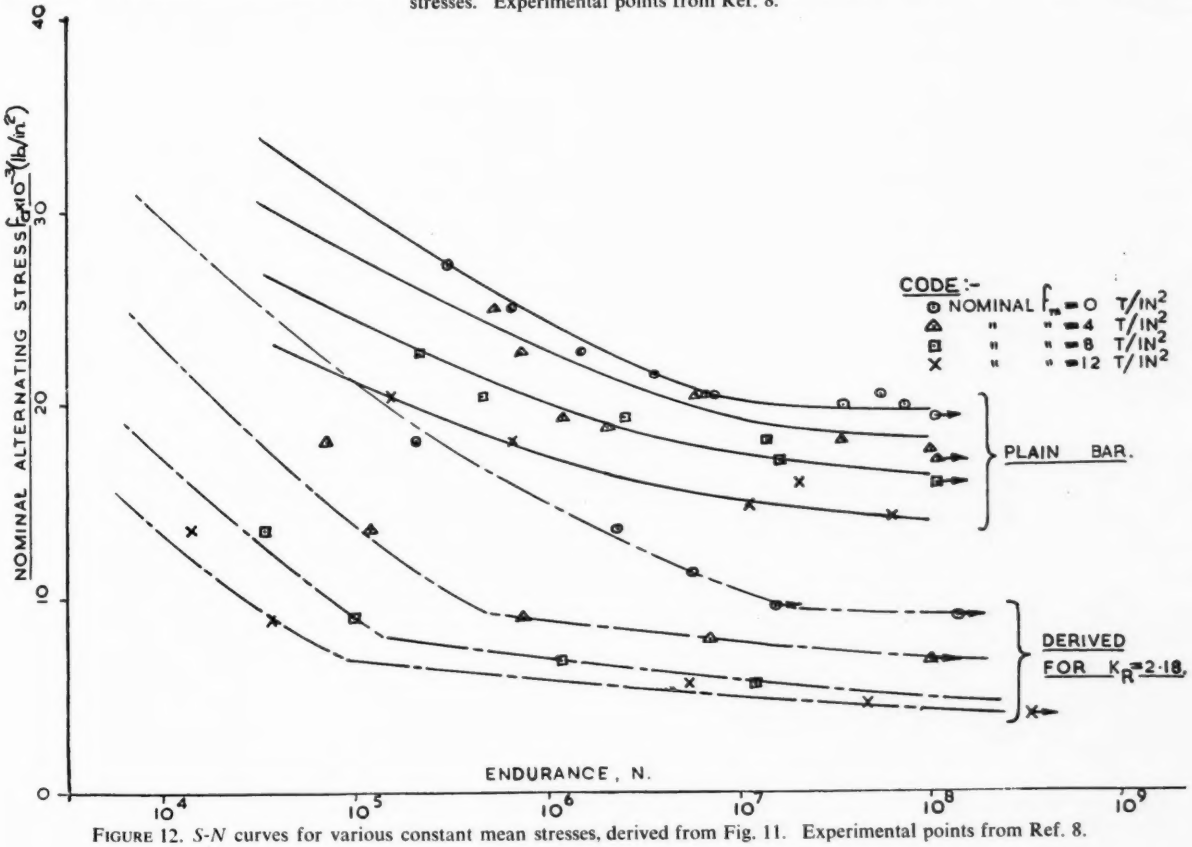
NOMINAL ALTERNATING STRESS $f_p \times 10^{-3}$ (lb/in^2)
ENDURANCE, N.
CODE :-
NOMINAL f_m = 0 T/IN^2
" " = 4 T/IN^2
" " = 8 T/IN^2
" " = 12 T/IN^2
PLAIN BAR.
DERIVED FOR K_R=2·18.

FIGURE 12. *S-N* curves for various constant mean stresses, derived from Fig. 11. Experimental points from Ref. 8.

for every element of the structure, irrespective of the stress level at the element.

A different type of loading is characterised by the pressure cabin, which may be loaded by two or more independent load systems; *e.g.* the pressurisation and the extraneous load system, comprising loads due to the aerodynamic forces upon the tail and wings.

With this type of loading, not only does the stress vary from point to point and from time to time, but also the loading parameter varies from point to point, so that a special treatment is necessary as will be described next.

To show the principles involved, an example will be worked without going into the details of allowance for plastic stress relief and scale effect. Suffice it to state without protracted discussion that if the basic data is obtained from direct-stress fatigue tests on *large* polished-bar specimens, and due allowance is made in the calculation for manufacturing defects which could reasonably be expected to occur in stressed regions, then neglect of the two factors mentioned will result in conservative estimates of the fatigue life (*i.e.* service life).

For the great majority of practical components, the point at which fatigue failure starts is at, or very near to an unloaded boundary, as the highest stresses occur at such locations.

Now on the periphery of such unloaded boundaries (*e.g.* holes) the directions of the major principal stress axes are everywhere tangential to the boundary, so that *on the boundary* the principal stresses due to separate loading systems are algebraically additive, and the *maximum* stresses may be found by direct superposition.

Figure 13 shows the general problem considered here, which is typified by a hole subjected to two distinct loading systems. If the structure is large, the stresses remote from the hole due to each load system can be regarded as a pair of orthogonal principal stresses, as shown.

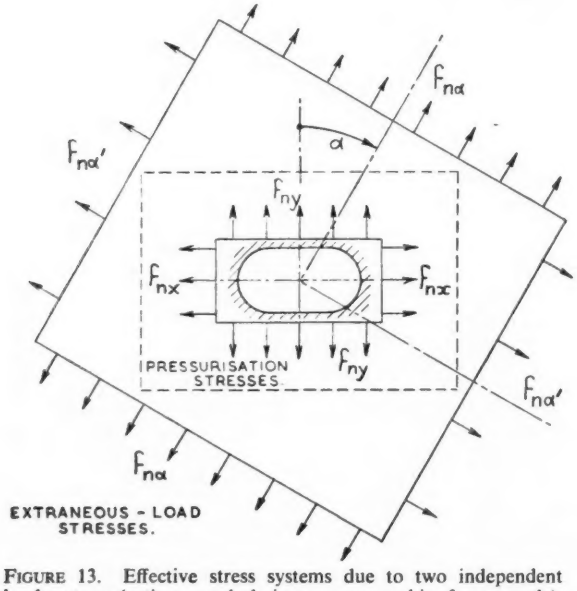

FIGURE 13. Effective stress systems due to two independent load systems (acting on a hole in a pressure cabin, for example).

For the example to be worked, the pressurisation loads are regarded as giving rise to the principal stresses f_{nx}, f_{ny} (*see* Fig. 13) while the extraneous load system causes the stresses $f_{n\alpha}$, $f_{n\alpha'}$ inclined as shown to the pressurisation system.

By standard stressing methods these two stress systems "remote from the hole" can be defined in terms of the loads on the structure; and in particular for a circular cylinder subjected to uniform internal pressurisation, the stresses f_{nx}, f_{ny} are in the ratio 1:2.

When a second system of loads acts on the strip, the stress system due to these extraneous loads may be considered as equivalent to a pair of orthogonal principal stresses "at infinity" inclined in general at angles α, α' $(=\alpha+\pi/2)$ to the y-axis, as shown in Fig. 13. By standard stressing practice the ratio of one of these stresses to the other will be known, and this ratio will be denoted here by $f_{n\alpha}:f_{n\alpha'}=1:A$.

For the present, the pressurisation stresses f_{nx}, f_{ny} will be regarded as constant in time, while the extraneous stresses $f_{n\alpha}$, $f_{n\alpha'}$ will be regarded as oscillating about a mean value. The mean part of $f_{n\alpha}$ will be written equal to $B\,.\,f_{ny}$, and the alternating component as $C\,.\,f_{ny}$.

On the hole boundary, the resultant principal stresses can be found by direct superposition of the stresses due to the separate imposed stress systems; where the stresses due to a system such as f_{ny} alone acting on a circular hole (Fig. 14) are given by:—

$$\widehat{\theta\theta}=f_{ny}\,(1-2\cos 2\theta) \qquad . \quad . \quad (5)$$

and the resultant system follows by addition for the appropriate angular positions.

The resultant stress at any point on the boundary at position θ is then given by

$$\widehat{\theta\theta}=f_{ny}\,(1-2\cos 2\theta)+f_{nx}\left[1-2\cos 2\left(\theta-\frac{\pi}{2}\right)\right]+$$
$$+f_{n\alpha}\,[1-2\cos 2\,(\theta-\alpha)\,]+f_{n\alpha'}\,[1-2\cos 2\,(\theta-\alpha')\,]\,. \qquad (6)$$

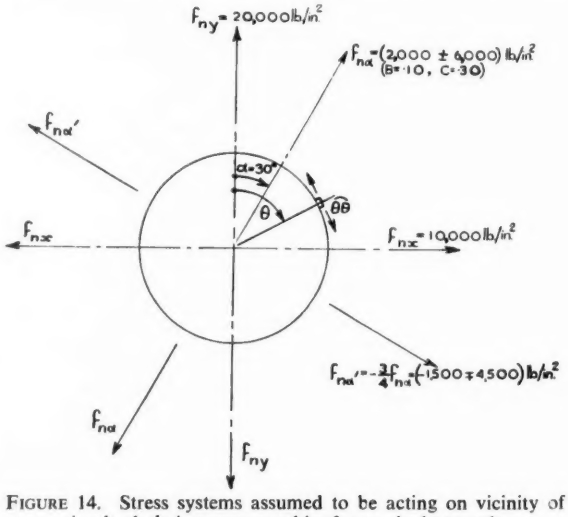

FIGURE 14. Stress systems assumed to be acting on vicinity of circular hole in pressure cabin, for worked example.

Substituting $f_{nx}=\frac{1}{2}f_{ny}$, $f_{n\alpha'}=A\,.\,f_{n\alpha}$ and $\alpha'=\alpha+\pi/2$ in equation (6)

$$\widehat{\theta\theta}=f_{ny}\left(\frac{3}{2}-\cos 2\theta\right)+f_{n\alpha}\left[(1+A)-2(1-A)\cos 2(\theta-\alpha)\right] \quad . \quad . \quad . \quad (7)$$

Now $f_{n\alpha}$, $f_{n\alpha'}$ has a constant component $B\,.\,f_{ny}$, and an alternating part $C\,.\,f_{ny}$, so that the fatigue stressing at the position θ may be written

$$\widehat{\theta\theta}=f_{ny}\left\{\left(\frac{3}{2}-\cos 2\theta\right)+B\left[(1-A)-2(1-A)\cos 2(\theta-\alpha)\right]\right\}\mp \pm f_{ny}\,.\,C\left[(1+A)-(2(1-A)\cos 2(\theta-\alpha)\right]\,. \quad . \quad (8)$$

where evidently the mean stress f_m is given by the first term in (8), or

$$f_m=f_{ny}\left\{\left(\frac{3}{2}-\cos 2\theta\right)+B\left[(1+A)-2(1-A)\cos 2(\theta-\alpha)\right]\right\} \quad . \quad . \quad . \quad . \quad (9)$$

and the alternating stress f_a is given by

$$f_a=\left|\,f_{ny}\,.\,C\left[(1+A)-2(1-A)\cos 2(\theta-\alpha)\right]\right|; \quad (10)$$

hence the loading parameter β at the point θ is given by

$$\beta\equiv\frac{f_m}{f_a}=\frac{\frac{3}{2}-\cos 2\theta}{C\left[(1+A)-2(1-A)\cos 2(\theta-\alpha)\right]}+\frac{B}{C} \quad . \quad (11)$$

The peak stress at the point θ is $f_p\equiv f_m+f_a$, which may be evaluated from equations (9) and (10).

From equations (9), (10) and (11), the loading parameter and the peak stress both vary round the periphery of the cut-out.

The scheme of calculation now is to find the endurance of the material at each of a series of points round the periphery, knowing the quantities f_p, β at each point, and using an endurance chart (*e.g.* Fig. 2) appropriate to the material used. The point of least endurance on the periphery then determines the problem.

To illustrate the scheme, some more or less arbitrary values will be assigned to the various applied stresses, and the angle α; and because the most complete endurance chart available is for 14 S-T (L. 65) material, it will be assumed that the part of the cabin considered is made of L.65 material or one of its many equivalents.

The calculations are set out in Table II.

From Table II it is clear that the point with minimum fatigue life in this example occurs near $\theta=115°$, with a life of 2,000 cycles of *extraneous loading*.

It can be seen that here the minimum-life point occurs near the point of maximum alternating stress, but in general it would be displaced from this point in the direction of increasing mean stress.

It should be noted that if the maximum alternating stress *alone* acted on the hole, the peak stress would be $1{\cdot}13\times f_{ny}$, or 22,600 lb./in.^{2}, which would result in a life of about $3{\cdot}6\times10^6$ cycles of extraneous loading ($\beta=0$, Fig. 2). Thus in this example the effect of the *constant components of load* is to reduce the endurance by a factor of 1,800—another example of the importance of the mean stress, and consequently of the loading parameter.

These calculations assume that the pressurisation load is constant in time, but in practice the pressurisation goes through one cycle (zero to full-load and back) per flight. This corresponds to a superimposed loading cycle with peak stress equal to the maximum pressurisation stress, and therefore $\beta=1$. In this example the maximum *pressurisation* stress is $2{\cdot}5\times20{,}000$ lb./in.^{2}, at $\theta=90°$, so that (from Fig. 2) the life under repeated pressurisation alone would be 10^5 cycles.

Since this loading cycle occurs only once per flight, this latter result would require a very large number of flying hours to cause failures; each pressurisation cycle being responsible (by the "cumulative damage" hypothesis) for only about ten millionths of the aircraft life.

Thus, testing under pressurisation alone would not only appear to indicate an extremely long flying life, but would also produce final failure at a point far

TABLE II

TABULAR CALCULATIONS FOR ESTIMATION OF FATIGUE LIFE OF A PRESSURE CABIN

Assumed data:—

$f_{ny}=20{,}000$ lb./in.^{2} $\quad\therefore f_{nx}=10{,}000$ lb./in.^{2}

$A=-\frac{3}{4}$, $\quad B=0{\cdot}10$, $\quad C=0{\cdot}30$, $\quad \alpha=30°$

Angle θ degrees	f_m/f_{ny} Equation (9)	f_a/f_{ny} Equation (10)	β Equation (11)	f_p/f_{ny} Equation (8)	f_p (*lb./in.*^{2}) Equation (8)	*N (cycles)* Fig. 2
0	0·350	0·450	0·778	0·800	16,000	∞
30	0·675	0·976	0·692	1·651	33,000	$5{\cdot}5\times10^6$
45	1·221	0·836	1·46	2·057	41,100	10^7
60	1·850	0·450	4·11	2·300	46,000	∞
90	2·700	0·600	4·50	3·300	66,000	$1{\cdot}8\times10^6$
100	2·734	0·880	3·11	3·614	72,300	$5{\cdot}8\times10^3$
105	2·695	0·986	2·735	3·681	73,600	$3{\cdot}2\times10^3$
110	2·621	1·064	2·46	3·685	73,700	$2{\cdot}9\times10^3$
115	2·520	1·130	2·23	3·650	73,300	$2{\cdot}0\times10^3$
120	2·375	1·126	2·11	3·501	70,000	$3{\cdot}0\times10^3$
135	1·829	0·986	1·86	2·815	56,300	10^5
150	1·200	0·600	2·00	1·800	36,000	$1{\cdot}7\times10^8$
180	0·350	0·450	0·778	0·800	16,000	∞

removed from the point of failure which would be found under the correct combined loading; indicating failure at $\theta=90°$ instead of $\theta=115°$.

This example thus serves to show that a very short service life may result from the superimposition of two systems of stress which, acting alone, would each allow a very long life. In particular, the significance of the pressurisation lies in the fact that it provides large magnitude of *mean stress* on which the oscillating components may be superimposed.

It follows from this that no test can be regarded as giving a reliable guide to the expected service life of a component unless both the steady and oscillating components of load are accurately represented.

For example; testing under an arbitrarily increased pressurisation alone, in the absence of flight loads, will *not* cover a pressurised structure for combined pressurisation and flight loads, except by accident.

In an actual problem, it may be impracticable to derive analytical expressions for the distribution of stress round a cut-out, but experimental methods of sufficient accuracy for this purpose exist.

Perhaps the most obvious method of approach is first to select the regions of high stress by means of brittle-lacquer testing and then to evaluate the stresses in these regions with the aid of strain gauges. In the experimental approach it will be necessary to test separately under conditions of pressurisation alone and extraneous forces alone, in order to construct the equivalent of Table II from the experimental measurements.

It is obvious that the present example has been simplified by the neglect of certain practical considerations, such as the curvature of the fuselage, local "spots" of stress concentration due to (say) rivets, and the influence of changes of skin thickness; but it is felt that the economic benefits to be derived from calculating fatigue life directly are so great that it would be a major economy in the long run to design aircraft with "stressable" stress concentrations only.

This implies that holes and cut-outs should be of elliptical form (although holes of more general form can be dealt with, *see* Ref. 1), and that local stiffening should be gently "grown" on to skinning, perhaps by the use of integral construction or adhesive bonding. In this way the stress distribution can be made to vary only slowly from point to point, and the danger of overlooking a bolt-hole can be eliminated.

It is of interest to note here that in general the cut-out of longest fatigue life is an ellipse with the major axis inclined *almost* in line with the greatest oscillating tensile stress, but rotated slightly in the direction of increasing mean stress. The ratio of major to minor axis depends on the particular stress systems encountered.

Another point of considerable interest is that (in the present example), the fatigue life associated with the cut-out would be multiplied by a factor of five by reducing every stress by 9 per cent. (*see* Fig. 2, $\beta=2{\cdot}23$); so that if the cabin had an unacceptable life when made of 0·036 inch sheet, the life could be increased by 500 per cent. by making it of 0·039 inch sheet. A change to 0·048 inch sheet would reduce the peak stress (Table II) from 73,300 lb./in.^{2} to 55,000 lb./in.^{2}, giving $N=4\times10^5$ cycles (Fig. 2); an increase in service life of 20,000 per cent! This is a significant commentary on the scatter of endurance observed on test.

Hence the methods illustrated above could be used with confidence to predict the necessary "general thickening" of a component found by test to be unsatisfactory, provided that *measured* stresses are used.

If *nominal* stresses were used for these estimations, allowance for plastic relief might be necessary at low endurances. If theoretical elastic stresses are used in calculation, the calculated life would be less than that found experimentally if plastic relief actually occurred, so that neglect of relief in a pure calculation gives an answer which may err on the safe side.

Scatter of Endurance

The scatter of endurance found in experimental fatigue testing is a matter of considerable significance when components are to be accepted for service on the results of a limited number of tests.

One suggestion is to stipulate that either the mean endurance or minimum endurance of components tested under the actual service loads shall be greater than the required service life by some factor (perhaps three), while another is to stipulate that the mean endurance shall be equal to that required in service when the component is tested under loads greater than the service loading.

The first of these suggestions leads to serious inconsistencies, as may be seen by reference to Fig. 15. This diagram represents the $\beta=1$ endurance curve for a notched component of L.65, with a scatter band sketched in. To fix ideas it will be supposed that this scatter band has been constructed systematically so that (for example) only one component in a hundred would give a result falling outside the band.

If the components were tested at a constant nominal stress of 30,000 lb./in.^{2} the variation of endurance represented by the width of the scatter band would be from 6,200 to 7,500 cycles, a ratio of 1 : 1·21.

At 10,000 lb./in.^{2} nominal stress, however, the scatter of endurance becomes $1{\cdot}2\times10^6$ to $4{\cdot}0\times10^6$ cycles; or a ratio of 1 : 3·34, while at a nominal stress of 7,400 lb./in.^{2}, where the endurance curve tends to become horizontal, the endurance ranges from 8×10^7 to infinity!

Difficulties of a similar nature arise when components made from different materials are to be covered by a single set of acceptance regulations, because the range of endurance at any given stress is very sensitive to differences in the slope of the endurance curve.

Thus the main difficulty about specifying a certain factor on life is that, to provide safety for operational conditions where the endurance curve has a small slope, the required factor on endurance would have to be large; resulting in excessive requirements for operational conditions where the endurance curve slopes steeply.

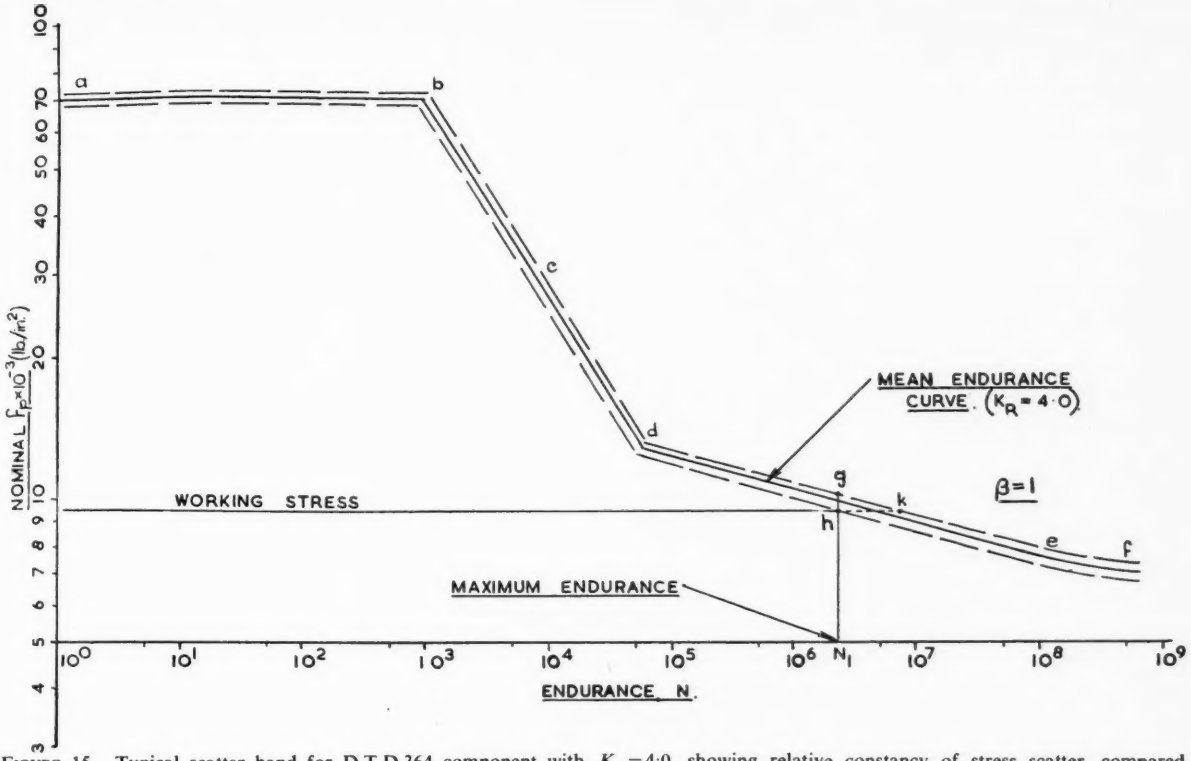

FIGURE 15. Typical scatter band for D.T.D.364 component with $K_R = 4{\cdot}0$, showing relative constancy of stress scatter, compared with endurance scatter.

If the course is taken of specifying test loads greater than the service loads, the potential economic penalties are very much reduced, provided that the chosen stress factor and required service life are specified carefully.

Furthermore, this method is much more suited to the philosophy required in the calculation of fatigue life, since the basic hypothesis of such calculations is that (for given β) a given peak stress in the component results in failure in a corresponding number of load cycles. If this hypothesis is used, the observed scatter of endurance must be regarded as a consequence of the fact that, for a component loaded to a given *nominal* stress, the *maximum* stress is subject to random variation.

This hypothesis is well suited to the calculation of fatigue life, and the associated scale effects, but the full discussion of these effects is outside the scope of the present paper.

The suggested methods for making allowance for endurance scatter may be summarised as follows:

(*a*) First establish suitable scatter-band widths by experiment, resulting in the establishment of limit endurance curves as shown in Fig. 15.

(*b*) Establish the *maximum* life to be required for any component of the series under consideration. It will then be expected that because of obsolescence, or similar causes, very few components will stay in service for that life.

(*c*) For components so expensive that only one can be tested, select nominal test stresses corresponding to the stress at the upper edge of the scatter band at the required endurance (*e.g.* *g*, Fig. 15), and stipulate that in no test shall the *minimum* endurance be less than the required endurance (*e.g.* N_1, Fig. 15).

This, in effect, stipulates that the components shall have a minimum reserve fatigue strength equal to the ratio of the stress ordinate at the upper and lower edges of the scatter-band (*g*, *h*, Fig. 15), and consequently the maximum margin of strength will be twice the minimum margin of strength.

For components which can be tested in greater numbers, the *mean* realised strength at the required life may be allowed to approach that corresponding to the middle of the scatter band of Fig. 15, where the point (N_1, *h*) defines the required maximum endurance and the working stress.

These rules should ensure that if the tested components comply with the rules, then less than one component in a hundred (for example, dictated by the chosen width of scatter band) will have an endurance less than the *maximum* envisaged for the service life; and obviously the probability of the coincidence of the weakest component with the longest-lived aircraft is then very small.

In practice, these rules can be reduced to simple numerical fatigue-strength factors, varying slightly with the number of components tested, and the material used.

Conclusions

A simple and convenient endurance chart for the presentation of comprehensive fatigue data has been described in some detail, and the application of the chart to calculations of fatigue life has been illustrated.

The chart shows clearly the effects of mean stress, residual stress and pre-tension, and is well suited to such extensions of utility as the comparison of different materials on a fatigue strength/weight ratio basis.

The simple examples illustrating the use of the chart were chosen to demonstrate the extent of the inaccuracies which may arise if fatigue calculations are attempted on a basis of incomplete data. In particular, it has been shown that calculations which fail to take proper account of the "loading parameter β $(=f_m/f_a)$" are liable to very large errors, particularly when the calculations concern notched components under high mean stresses.

One incidental point which becomes obvious from the endurance chart is the fact that a "high-strength" aluminium alloy may in certain conditions have less fatigue strength than a more conventional alloy.

Another point of interest which can be discerned is the definite tendency for the endurance curves of aluminium alloys to flatten out at high endurances.

A tentative construction has been proposed which appears to afford reasonably accurate representation of the effects of plastic stress-concentration relief in notched components. This construction, if confirmed or refined, will allow the construction of the complete endurance curves for any notched component, right from the case of static failure at $N=1$ cycle through to $N=10^9$ cycles, or even infinity.

A simple example has been worked to show the scheme of calculation for a component loaded by two independent loading systems, the example chosen representing a cut-out in a pressure cabin.

Although the figures taken for this example were arbitrary, it is possible to draw some general conclusions from it. Thus, the results show that, although a component may have a very long life under either loading system acting alone, the life may be extremely short when the two systems act together. In the example, the pressurisation affected the life primarily by providing a high level of mean stress upon which the oscillating part of the extraneous loading was superimposed.

Furthermore, testing under either load system alone would produce fatigue failure at a point far removed from the point of failure under the combined load systems.

The scheme of calculation shown would be amenable to the estimation of fatigue life from stress measurements, for any component in which the principal axes of the maximum stresses are aligned in a constant direction.

The methods outlined here were first propsed in an unpublished report[2], where the related aspects of fatigue life calculations are discussed in some detail.

Acknowledgment

The opinions expressed are those of the author and do not necessarily represent the views of Hawker Aircraft Ltd. The author wishes to express his thanks to Sir Sydney Camm, Director and Chief Designer, for permission to publish this paper.

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TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Unsteady Isentropic Flow with Variable Specific Heats

by

R. S. BENSON, M.Sc.(Eng.), A.M.I.Mech.E.

(*Lecturer in Mechanical Engineering, University of Liverpool*)

IT IS USUAL when plotting characteristic diagrams for unsteady flow fields to assume a constant ratio of specific heats. In the general theory of characteristics developed by Guderley[1] the variable specific heats are introduced into the calculation of the characteristic constants. In the following method the variation in the ratio of the specific heats is included directly into the slope of the state characteristics. The position diagram may then be plotted directly by the usual techniques[2].

The general characteristic solutions for one-dimensional frictionless flow are:

The direction conditions $$\frac{dx}{dt} = u \pm a \quad . \quad . \quad . \quad (1)$$

and the consistency or compatibility conditions

$$\frac{dp}{d\rho} = \mp \rho a. \quad . \quad . \quad . \quad . \quad (2)$$

The direction of the characteristics in the state $(a-u)$ diagram can be obtained from equation (2) for isentropic flow by the use of the following equations.

$$ds = c_p \frac{dT}{T} - R\frac{dp}{p} = 0 \quad . \quad . \quad . \quad (3)$$

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s = \frac{dp}{d\rho} = \gamma RT \quad . \quad . \quad (4)$$

$$\frac{p}{\rho} = RT \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\frac{c_p}{R} = \frac{\gamma}{\gamma - 1} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where
- p pressure
- ρ density
- T temperature
- s entropy
- u velocity
- a speed of sound
- R gas constant
- γ ratio of specific heats
- c_p specific heat at constant pressure

c_p and γ are functions of temperature only.

Differentiating equation (4) with respect to T and noting

$$\gamma = \gamma(T), \quad a = a(T), \quad \gamma = \gamma(a)$$

we get

$$\left[2 - \frac{d\gamma}{da}\frac{a}{\gamma}\right]\frac{da}{dT} = \frac{\gamma R}{a} \quad . \quad . \quad . \quad (7)$$

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Substituting for dT in equation (3) and then for dp in equation (2) the slope of the state characteristics is obtained.

$$\frac{da}{du} = \mp \frac{\gamma - 1}{2}\left[\frac{1}{1 - \frac{a}{2\gamma}\frac{d\gamma}{da}}\right] \quad . \quad . \quad (8)$$

Since $\gamma = \gamma(a), \quad \frac{d\gamma}{da} = \phi(a)$

the slope of the state characteristics will be continually varying, thus the state diagram will consist of a series of parallel curves. If a fine characteristic mesh is used, the curves may be replaced by a series of straight lines each with a mean slope corresponding to equation (8). The slope may be obtained directly for any value of A by the use of the auxiliary curve (Fig. 1). The curve is constructed by drawing radial lines from the point $A = 1 U = -1$ to intersect with the value of A corresponding to the value of the slope. The locus of the intersecting points gives the curve. To obtain the slope at any value

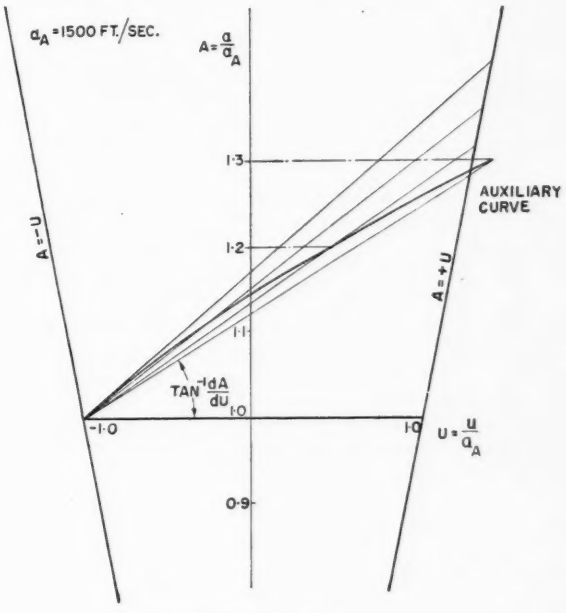

FIGURE 1. State diagram.

of A a line is drawn from the point $A=1U=-1$ to the intersection of the curve and the value of A.

In non-dimensional form equation (8) is

$$\frac{dA}{dU} = \mp \frac{\gamma-1}{2}\left[\frac{1}{1-\dfrac{A}{2\gamma}\dfrac{d\gamma}{dA}}\right] \quad . \quad . \quad (9)$$

where $A=\dfrac{a}{a_A}$, $U=\dfrac{u}{a_A}$

a_A reference speed of sound.

The function $\dfrac{a}{2\gamma}\dfrac{d\gamma}{da}$ is unique for each gas. Fig. 2 shows the variation of γ with the speed of sound a for air; on the same graph equation (8) is plotted against a.

For calculations in which the range of temperature consequent on wave action is fairly small, the ratio of specific heats may be assumed constant. For calculations in which the temperature range is fairly large, equation (8) should be evaluated to ascertain the likely range of the characteristic slope.

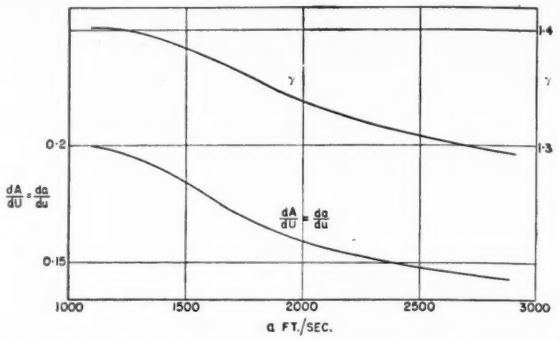

FIGURE 2. Variation in γ and state characteristic slopes with speed of sound for air.

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Determination of Velocity and Pressure Distribution along the Surface of Annular Aerofoils with Thick Symmetrical Sections

by

SVETOPOLK PIVKO

(Aerotechnical Institute, Beograd-Zarkovo, Yugoslavia)

AN APPROXIMATE method is shown for the estimation of the velocity and pressure distribution over the surface of circular annular aerofoils with thick symmetrical sections, at zero incidence.

METHOD

Figure 1 shows an annular aerofoil or profiled ring obtained when an aerofoil with symmetrical section rotates about an axis.

From the theory of wing sections it is known[1] that the aerodynamic effect of a symmetrical aerofoil section, at zero angle of attack, may be approximately replaced by the effect of sources and sinks distributed along the chord of the section.

The strength dQ of a single source or sink can be related to the shape by

$$\frac{dQ}{dx} = 2V_0\frac{dr}{dx} \quad . \quad . \quad . \quad . \quad (1)$$

where V_0 is the velocity of the undisturbed stream, and r is the ordinate of the symmetrical aerofoil section at distance x from the leading edge.

The aerodynamic effects of a cylindrical annular aerofoil with symmetrical section, at zero incidence, may therefore be approximately replaced by a system of the source-sink rings, having the strength

$$\frac{dQ}{dx} = 4\pi V_0\frac{dr}{dx} \quad . \quad . \quad . \quad . \quad (2)$$

and distributed on the surface of a cylinder of radius R.

The axial and radial components of the velocity induced at the point (x, R) by a source ring, or by a distribution of sources of constant strength dQ along a circle of radius R, situated at the distance x_0 from the leading edge, may be obtained from the expressions

$$v_{qx}(x-x_0, R) = \frac{dQ}{2\pi R}\, v'_{qx}{}^* \quad . \quad . \quad (3)$$

$$v_{qr}(x-x_0, R) = \frac{dQ}{2\pi R}\, v'_{qr}{}^* \quad . \quad . \quad (4)$$

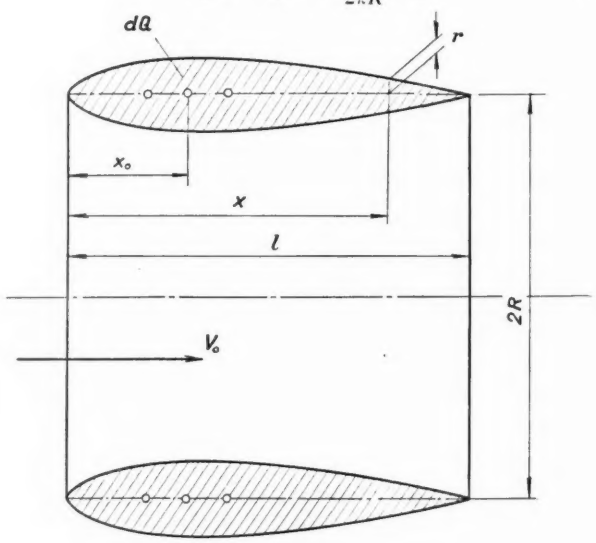

FIGURE 1.

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The values v_{qx}^* and v_{qr}^* were tabulated by Küchemann and Weber[2].

Substituting for dQ from (2), the components of the velocity induced at the point (x, R) by a distribution of source-sink rings are

$$\frac{v_x(x,R)}{V_0} = \frac{2l}{R}\int_0^1 \left(\frac{dr}{dx}\right)_{x=x_0} v_{qx}^*(x-x_0, R)\, d\left(\frac{x}{l}\right) \quad (5)$$

$$\frac{v_r(x,R)}{V_0} = \frac{2l}{R}\int_0^1 \left(\frac{dr}{dx}\right)_{x=x_0} v_{qr}^*(x-x_0, R)\, d\left(\frac{x}{l}\right) \quad (6)$$

where l is the length and R the radius of the annular aerofoil shown on Figure 1 and replaced by source-sink rings.

At small thickness of the sections the velocity induced on a cylinder is approximately the same as it would be if induced on the surface of the annular aerofoil.

Then the local stream velocity on the surface can be expressed by

$$V = [(V_0 + v_x)^2 + v_r^2]^{\frac{1}{2}}. \quad (7)$$

The direction of flow must be parallel to the surface, thus

$$\frac{dr}{dx} = \frac{v_r}{V_0 + v_x}. \quad (8)$$

The condition that the trailing edge shall close is given by

$$\int_0^l dr = \int_0^l \frac{dr}{dx}\, dx = 0 \quad (9)$$

or

$$\int_0^l \frac{v_r}{V_0 + v_x}\, d\left(\frac{x}{l}\right) = 0. \quad (10)$$

The pressure distribution along the surface of the annular aerofoil can be obtained from

$$C_p = 1 - \left(\frac{V}{V_0}\right)^2 = 1 - \left(1 + \frac{v_x}{V_0}\right)^2 - \left(\frac{v_r}{V_0}\right)^2. \quad (11)$$

REMARKS

It may be noted that the integrations in equations (5) and (6) can only be done numerically. The components of the induced velocity to satisfy the conditions (8) and (10) for a given shape can be obtained by successive approximations. It is evident, therefore, that the estimation of the velocity or pressure distribution over the surface of the annular aerofoil represents a tedious process.

As the sections of the annular aerofoils are usually thin, it would usually be sufficient to use a method which is comparatively rapid and easy to apply, but which will give only rough approximate results.

In numerical examples[3] it has been found that the local velocity increment on the surface of the annular aerofoil with symmetrical sections is approximately the same as that in the two-dimensional flow around an aerofoil, having the same shape but multiplied by the value of 2π.

Hence, for the annular aerofoil with symmetrical sections, the local velocity distribution may be obtained approximately from

$$\frac{V'}{V_0} \approx 1 + 2\pi\left(\frac{v}{V_0} - 1\right). \quad (12)$$

where v is the local velocity about a symmetrical aerofoil in the two-dimensional flow, at zero angle of attack.

For N.A.C.A. aerofoils, the values of v are given in Ref. 4. For other aerofoils, these values may be determined using the method shown in Ref. 1.

NUMERICAL EXAMPLE

Figures 2, 3 and 4 show the results of calculations for the annular aerofoil with the ratio length-diameter $l/2R = 1{\cdot}0$, obtained by rotating the symmetrical aerofoil N.A.C.A. 64010 around an axis.

The ordinates r and the velocities v for the N.A.C.A. 64010 base aerofoil are given in Ref. 4. The values v_{qx}^* and v_{qr}^*, used in equations (3) and (4) are found in Ref. 2.

The axial and radial components of the velocity induced by a distribution of source-sink rings, determined by means of numerical integration using equations (5) and (6) are plotted in Fig. 2. So that the desired velocity distribution will represent a real aerofoil which closes and has a sharp trailing edge, the condition (10) must be satisfied. The curve v_r is therefore adjusted in the region of the trailing edge—dotted line in Fig. 2.

Figures 3 and 4 show the velocity and pressure distribution along the surface of the considered annular aerofoil. The values calculated by using equation (7)—full lines *a*—are plotted along with those calculated from the approximate equation (12)—dotted lines *b*.

The velocity and pressure distributions corresponding to the two-dimensional flow around the N.A.C.A. 64010 section, at zero angle of attack—dotted curves *c*—are also shown for comparison.

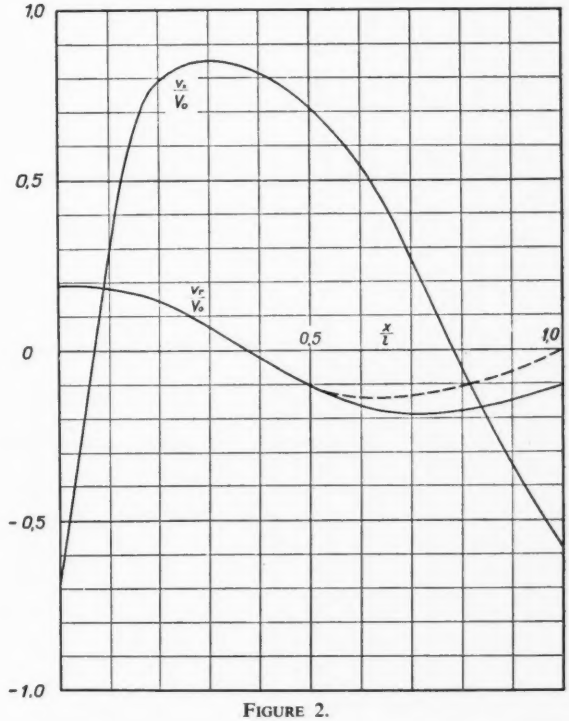

FIGURE 2.

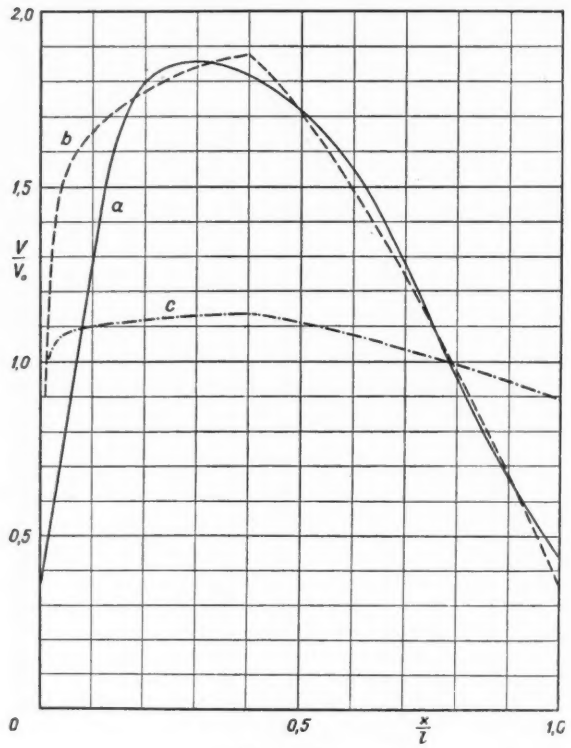

FIGURE 3.

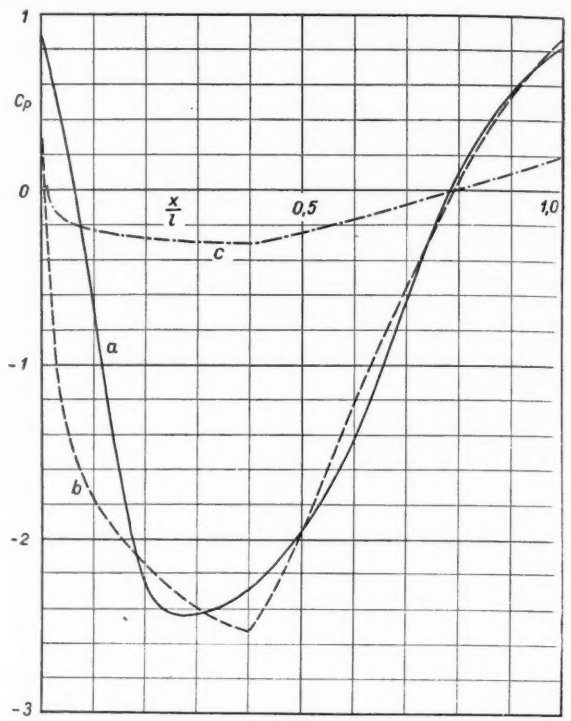

FIGURE 4.

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Numerical Solution of n *Linear Equations in* n *Unknowns, and the Evaluation of* nth *Order Determinant (Complex Coefficients)*

by

D. W. ALLEN, B.A.

A PRESENTATION of the solution of linear equations with complex coefficients is given, in which current checks can be introduced to obviate inaccuracies and thus engender confidence in use. The method is based on the elementary concept of elimination of each unknown in turn, and details only of its application are given since the theory demands lengthy exposition. Evaluation of determinants is also illustrated.

1. GENERAL

The equations may be written

$$\sum_{s=1}^{n} (a_{rs} + ib_{rs})\, x_s = a_{r\,(n+1)} + ib_{r\,(n+1)}; \quad (r = 1, 2 \ldots\ldots n).$$

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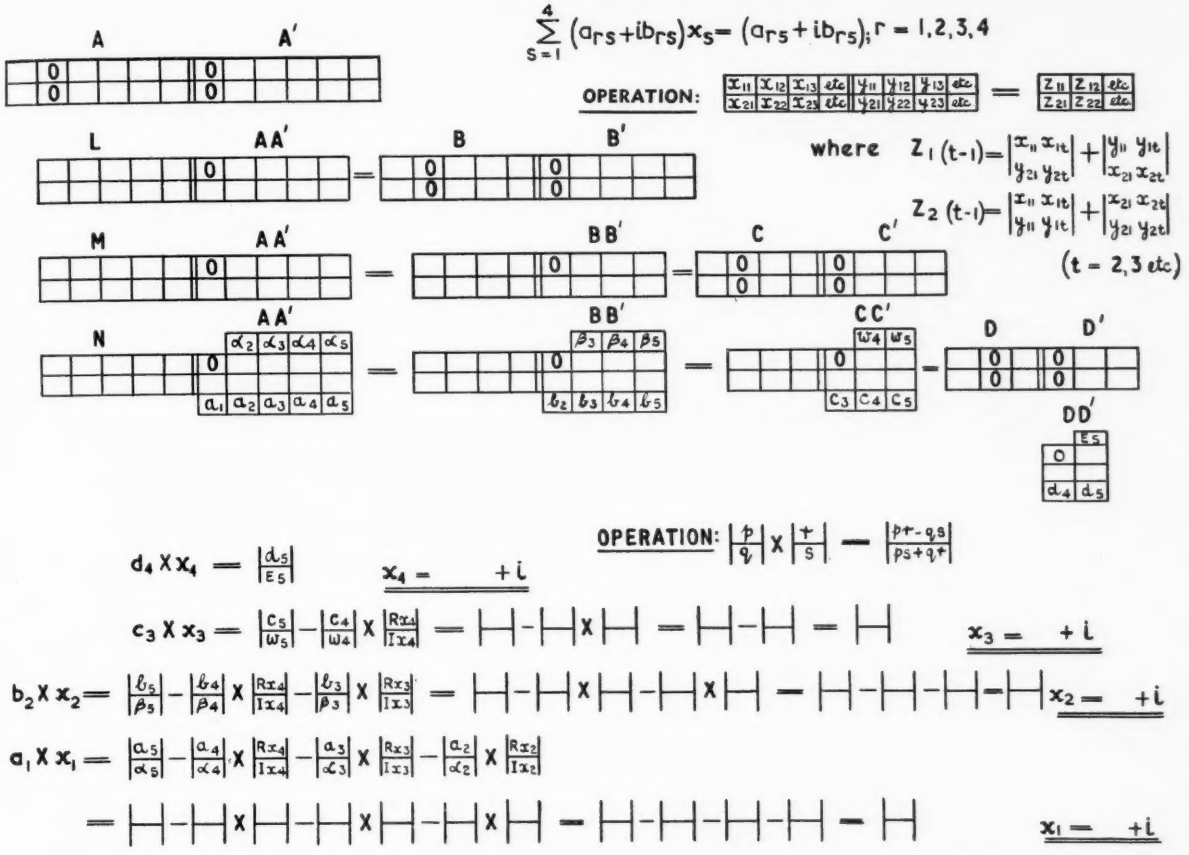
The steps leading to the solution are divided into two parts:

(*i*) The elements of two arrays are combined to form the elements of another array by the addition of two second order determinants:—

x_{11}	x_{12}	x_{13}	etc.	y_{11}	y_{12}	y_{13}	etc.	=	z_{11}	z_{12}	etc.
x_{21}	x_{22}	x_{23}	etc.	y_{21}	y_{22}	y_{23}	etc.		z_{21}	z_{22}	etc.

where $$z_{1\,(t-1)} = \begin{vmatrix} x_{11} & x_{1t} \\ y_{21} & y_{2t} \end{vmatrix} + \begin{vmatrix} y_{11} & y_{1t} \\ x_{21} & x_{2t} \end{vmatrix}$$

and $$z_{2\,(t-1)} = \begin{vmatrix} x_{11} & x_{1t} \\ y_{11} & y_{1t} \end{vmatrix} + \begin{vmatrix} x_{21} & x_{2t} \\ y_{21} & y_{2t} \end{vmatrix} \quad (t = 2, 3 \ldots\ldots).$$


A
A′
$\sum_{s=1}^{4} (a_{rs}+ib_{rs})x_s = (a_{rs}+ib_{rs}); r = 1,2,3,4$
OPERATION:
where $Z_1(t-1) = \left|\begin{matrix} x_{11} & x_{1t} \\ y_{21} & y_{2t} \end{matrix}\right| + \left|\begin{matrix} y_{11} & y_{1t} \\ x_{21} & x_{2t} \end{matrix}\right|$
$Z_2(t-1) = \left|\begin{matrix} x_{11} & x_{1t} \\ y_{11} & y_{1t} \end{matrix}\right| + \left|\begin{matrix} x_{21} & x_{2t} \\ y_{21} & y_{2t} \end{matrix}\right|$
$(t = 2,3 \text{ etc})$
L
AA′
B
B′
M
AA′
BB′
C
C′
N
AA′
BB′
CC′
D
D′
DD′
OPERATION: $\left|\frac{p}{q}\right| \times \left|\frac{r}{s}\right| = \left|\frac{pr-qs}{ps+qr}\right|$
$d_4 X x_4 = \left|\frac{d_5}{E_5}\right|$
$x_4 = \quad +i$
$c_3 X x_3 = \left|\frac{c_5}{w_5}\right| - \left|\frac{c_4}{w_4}\right| X \left|\frac{Rx_4}{Ix_4}\right|$
$x_3 = \quad +i$
$b_2 X x_2 = \left|\frac{b_5}{\beta_5}\right| - \left|\frac{b_4}{\beta_4}\right| X \left|\frac{Rx_4}{Ix_4}\right| - \left|\frac{b_3}{\beta_3}\right| X \left|\frac{Rx_3}{Ix_3}\right|$
$x_2 = \quad +i$
$a_1 X x_1 = \left|\frac{a_5}{\alpha_5}\right| - \left|\frac{a_4}{\alpha_4}\right| X \left|\frac{Rx_4}{Ix_4}\right| - \left|\frac{a_3}{\alpha_3}\right| X \left|\frac{Rx_3}{Ix_3}\right| - \left|\frac{a_2}{\alpha_2}\right| X \left|\frac{Rx_2}{Ix_2}\right|$
$x_1 = \quad +i$

Solution of linear algebraic equations (complex coefficients).

(*ii*) One root is found immediately by division in the final array, and the other solutions follow from the sum of products of complex numbers and a division.

To assist in computation $\left|\frac{p}{q}\right|$ symbolising a complex number is introduced where the value in the numerator is the real part and the denominator the imaginary.

Thus $\left|\frac{p}{q}\right| \times \left|\frac{r}{s}\right| = \left|\frac{pr-qs}{ps+qr}\right|$. Also $\Sigma \left|\frac{p_r}{q_r}\right| = \left|\frac{\Sigma p_r}{\Sigma q_r}\right|$.

A computing sheet for the case $n=4$ is given whose form of presentation is such that the scheme can be generalised. There would be n columns of twin-arrays in the first stage, the top row of each pair containing $(n+2)$, $(n+1)$, n . . . . . 3 elements respectively, and the printed zeros would be retained in their same positions relative to the left-hand end of each array, while the second stage of the solution would have n rows.

2. APPLICATION ($n=4$)

(1) Enter a and b coefficients in order in A, L, M, N (real parts on top row, imaginary on second), ignoring printed zero column in A.

(3) Obtain A' by copying elements of A in order, ignoring printed zero column.

(4) Following operations indicated on computing sheet evaluate AA' (taking into account printed zero columns in A and A'), and write results in the (three) appropriate arrays.

(6) Work out $L.AA'$, entering answers in vacant columns of B; then $M.AA'$ and $N.AA'$.

(8) B' is found from B in the same way as A' from A, and whole cycle of operations repeated until DD' is evaluated.

(9) Following second series of operations roots are found.

3. NUMERICAL CHECK ON ACCURACY

An additional column is appended to right-hand end of each array; steps (2), (5) and (7) are inserted in previous section, and (10) added.

(2) In check columns of A, L, M, and N record algebraic sum of a's and b's appropriate to the row.

(5) Check that the last pair of elements in AA' equals the algebraic sum of the horizontal elements preceding it.

(7) Apply the same check as before to B, and after completion of each successive array.

(10) In the final series of operations check values of the "roots" are found by replacing suffix $(n+1)$ coefficients by elements in the corresponding check columns. The "roots" should then be greater by 1 than the actual values of the roots.

Thus after each short series of operations a check on the accuracy of the work comes into play, and an error is quickly detected and eradicated.

EXAMPLE

A simple example is given using check columns.

$$(1-i)\,x_1+(1+i)\,x_2=4$$

$$(1+i)\,x_1-ix_2=-1+i$$

					A				A'
1	0	1	4	6	0	1	1	4	6
−1	0	1	0	0	0	−1	1	0	0

						AA'		
	L				α_2	α_3	$\alpha_{3'}$	
1	0	−1	0	0	2	4	6	=
1	−1	1	1	2	0	4	6	
				a_1	a_2	a_3	$a_{3'}$	

	B				B'			
=	−2	0	2	0	0	−2	2	0	=
	4	0	6	10	0	4	6	10	

	BB'	
	β_3	$\beta_{3'}$
0	−20	−20
20	20	40
b_2	b_3	$b_{3'}$

$$b_2x_2=\left|\frac{b_3}{\beta_3}\right| \quad x_2=1-i.$$

$$a_1x_1=\left|\frac{a_3}{\alpha_3}\right|-\left|\frac{a_2}{\alpha_2}\right|\times\left|\frac{Rx_2}{Ix_2}\right|$$

$$2x_1=\left|\frac{4}{4}\right|-\left|\frac{0}{2}\right|\times\left|\frac{1}{-1}\right|=\left|\frac{4}{4}\right|-\left|\frac{2}{2}\right|=\left|\frac{2}{2}\right| \quad x_1=1+i$$

$$b_2x_{2'}=\left|\frac{b_{3'}}{\beta_{3'}}\right| \quad x_{2'}=2-i=1+x_2$$

$$a_1x_{1'}=\left|\frac{a_{3'}}{\alpha_{3'}}\right|-\left|\frac{a_2}{\alpha_2}\right|\times\left|\frac{Rx_{2'}}{Ix_{2'}}\right|$$

$$2x_{1'}=\left|\frac{6}{6}\right|-\left|\frac{0}{2}\right|\times\left|\frac{2}{-1}\right|=\left|\frac{6}{6}\right|-\left|\frac{2}{4}\right|=\left|\frac{4}{2}\right|$$

$$x_{1'}=2+i=1+x_1.$$

4. COMPARISON WITH CROUT'S METHOD

Each element in a particular array is calculated independently of its other elements. In Crout's method, however, terms in a row are not independent so that when an error is detected all terms (both real and imaginary parts) subsequent to the erroneous term, once it has been located and corrected, need to be recalculated with the attendant risk of further error before the check is satisfied.

The method described here involves more operations than Crout's and $n=4$ sets the practical limit. The additional operations δ number

$2\{n(n-2)+(n-1)(n-3)+\ldots\}$ with check

and

$2\{(n-1)(n-2)+(n-2)(n-3)+\ldots\}$ without check.

n/δ	With check	Without check
3	6	4
4	22	16

5. DETERMINANTS

A computing sheet embodying the current check is given for a 4th order determinant, which may be evidently adapted to order n. The initial series of operations are as in solving linear equations. The determinant having been reduced to a triangular form the final step is the multiplication of n complex numbers and division by a constant, a process which is tabulated for completeness on the computing sheet. The initial columns of A, B, C and D are entered in P and Q in any order and PQ evaluated. Division by a^3b^2c then produces the numerical result. In general the constant is for

nth order determinant	$a^{n-1}b^{n-2}c^{n-3}\ldots\ldots p^3q^2r$
$(n-1)$th order	$a^{n-2}b^{n-3}c^{n-4}\ldots\ldots p^2q$
4th order	a^3b^2c
3rd order	$a^2b.$

The algebraic sign is determined by

$(-1)^{n/2}$, if n is even,

$(-1)^{\frac{n-1}{2}}$, if n is odd.

6. EXAMPLE

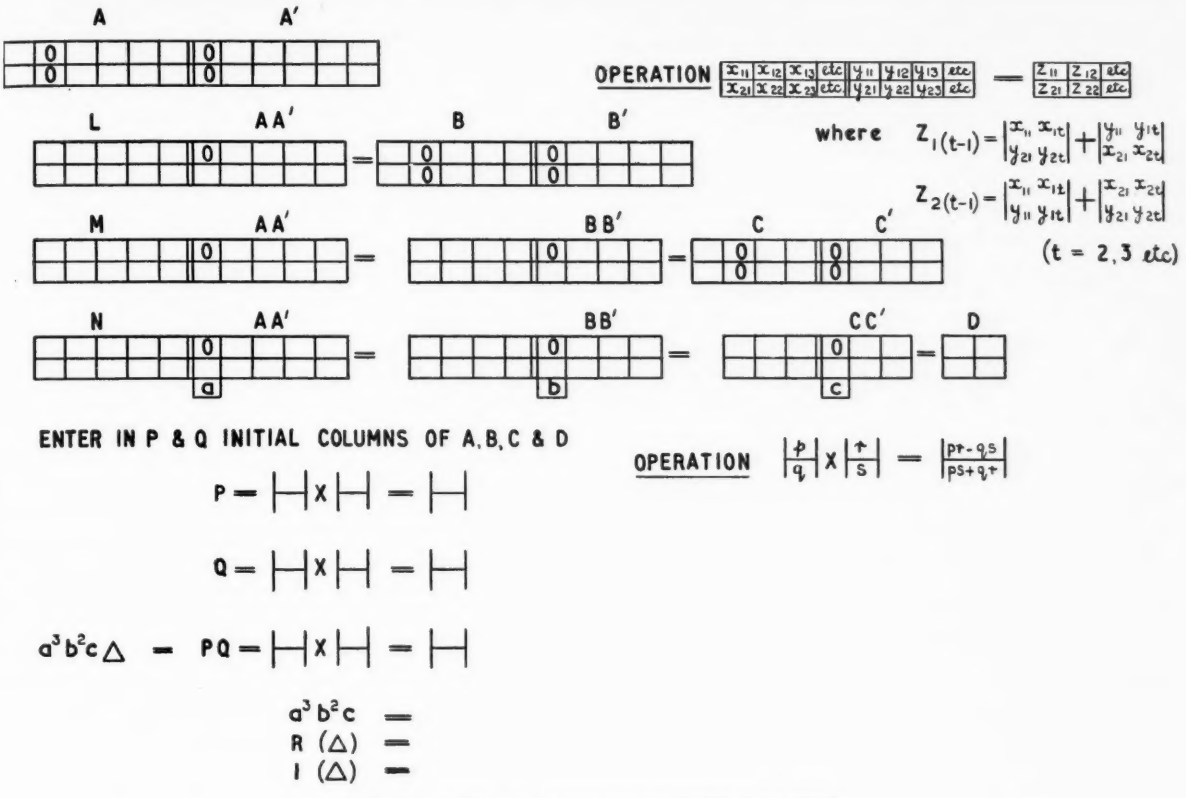
A 3rd order determinant is evaluated using check columns.

$$\Delta=\begin{vmatrix} 1+i & 2 & 1+i \\ i & i & -1+i \\ 1-i & 1+i & 1 \end{vmatrix}$$

					A				A'
1	0	2	1	4	0	1	2	1	4
1	0	0	1	2	0	1	0	1	2

					L		AA'		
0	0	−1	−1	0	−2	0	−2		
1	1	1	3	2	2	2	6	=	

					B				B'
=	2	0	2	4	0	2	2	4	
	0	0	0	0	0	0	0	0	



Evaluation of 4th order determinant (complex coefficients).

$$\begin{array}{|cccc||c|cc|c|}\hline 1&1&1&3&0&-2&0&-2\\ -1&1&0&0&2&2&2&6\\ \hline\end{array}\quad a$$

M AA' $=$

$$=\begin{array}{|cccc||c|cc|c|}\hline -2&0&-2&0&0&0\\ -6&-2&-8&4&4&8\\ \hline\end{array}\quad b \quad =\begin{array}{|cc|}\hline -8&-8\\ -16&-16\\ \hline\end{array}$$

BB' C

"Multiplying" initial columns of A, B and C

$$\left|\frac{1}{1}\right| \times \left|\frac{2}{0}\right| \times \left|\frac{-8}{-16}\right| = \left|\frac{2}{2}\right| \times \left|\frac{-8}{-16}\right| = \left|\frac{16}{-48}\right|$$

$$a^2b = 2^2 \times 4 = 16$$

$$a^2b\Delta = (-1)^{\frac{n-1}{2}} \left|\frac{16}{-48}\right|$$

$$\Delta = (-1)(1-3i) = -1+3i.$$

7. CONCLUSION

A method for solving linear equations and determinants with complex coefficients is given, which is also applicable with real coefficients only. After each short series of independent operations numerical accuracy can be checked.

The mathematical implication of zeros arising in the work has not been discussed since in a practical case they rarely occur, and may in general be avoided by suitable rearrangement in the initial set of equations.

Graduates' and Students' Section

This page of the Journal is written by members of the Committee of the Graduates' and Students' Section. It covers matters of interest and importance to Graduates and Students and previews lectures and visits.

—This month we have a "guest editorial" from Mr. A. V. Cleaver, F.R.Ae.S., which he has called:—

FOOD FOR THOUGHT

YOUR CHAIRMAN recently heard me holding forth on the following lines, and responded with a challenge to have the courage of my convictions and submit them to you in cold print. To any suggestion that they are inappropriate in this sober technical Journal, he and I might reply that such a view is stodgy and old-fashioned in an age which has demonstrated, above all, that technology and social conditions are inextricable.

We have recently heard many criticisms of British aviation (some of them valid) and many suggestions (some of them sensible) for putting right what is wrong. But has this been the whole story, and are such troubles confined to the Aircraft Industry? I think not; in fact, I believe our troubles are only one specialised manifestation of a national *malaise*.

An impression is abroad that the world owes us a living (it doesn't, unless we earn it): a complacency that there'll always be an England (there won't, if Englishmen don't wake up): a smug assurance that if it's British, it's best (it won't be, unless we make it so). An attitude of "take-it-or-leave-it" is considered quite in order towards customers or employers. Workers in the shipbuilding industry think they can afford to hold up the job for months of squabbling about which of them should drill the holes in certain panelling; those in the motor industry, working short time, consider that "they" should pay them the same wages as for a full week. If the cost of living rises, earnings should automatically increase, so that no inconvenience is suffered by anyone (except "they"?); every individual has a right to all the benefits of the Welfare State (an admirable conception, but one demanding certain conditions for it to be practical).

This is cloud-cuckoo land; the real, hard, world is not like that. It is still fiercely competitive, on the battlefields of both war and peace. Consider the new American jet liners; also the Tu.104, which is not magic, but is another indication that we have no divine right to pre-eminence even in those fields we pioneered. (And don't believe that one about how they were able to do it only because they captured some Germans, either). We, and our masters, must abandon any silly ideas (dating from the days of fabric-covered, piston-engined, biplanes—even if they were true then) that one ingenious Englishman is always equivalent to ten Americans or Russians with lavish equipment and resources. The unkind truth is that "they," like Santa Claus, don't exist. The only "rights" anyone can expect, in the long run, are those he earns. The lives of men, industries and communities obey the same basic law as machines; one can never get more out than one puts in.

There are those who will tell you that all these illusions are inseparable from an era of full employment. If we are not to accept such a depressing view of human nature, we must replace the fear of losing one's job with some other incentive; otherwise, the era of full employment will surely soon come to an end, and the cynics' solution will then be the only possible one. The alternative is a developed social consciousness, a satisfaction in doing a job well for its own sake, and a willingness to accept personal responsibility and be judged by the results achieved by the team in which one works.

What has all this to do with the Society's present Graduates and Students?

First, since it will take many years to bring about the required changes, it is a matter which must greatly concern them. In our industry, theirs is the task of doing better than most of their fathers and older brothers.

Secondly, having grown up in a decade during which such false ideas became current, they can perhaps hardly be blamed for adopting them. However, instead of accepting these standards of their times, it would have been better if they had been contemptuous of them.

Enterprise, enthusiasm and initiative are the proper qualities of youth, aiming self-critically at a high absolute standard, not blindly adjusting to the mediocre norm. ("That's all *they* do. Why should *I* be expected to do better?") If a special effort is expected from you, don't react to such a situation with mild indignation or resentment: take it as a compliment and a challenge. Doing a job well does not mean just putting in the hours (including paid overtime); it means doing it with speed, care, accuracy, and the full application of intelligence. (Giving value for money, in fact). That way, there lies more contentment and less frustration; less tiredness, not more.

The modern trend towards more scholarships, more time off for study for apprentices, and better pay and working conditions for young aeronautical engineers, is wholly to be encouraged—and always has been, to the full extent of his limited ability, by the present writer. However, it must not be taken for granted; it demands a great deal in return, if these things are to be maintained, and still further improved.

Finally, while it is entirely reasonable for young men to expect a lead from their superiors, remember that this again is a matter for give and take. The older man is also human; if the response is disappointing, he also can come to feel: "Oh, what's the use . . . ."

—A.V.C.

(Correspondence on this subject will be welcomed.
—Chairman.)

VISITS:

CANCELLED—U.S. 3rd AIR FORCE MANSTON 19th MAY—We have heard from the U.S.A.F. that they will have to cancel our visit to the Third Air Force at Manston which had been arranged for Saturday 19th May. Unfortunately posters for this had already been sent out but they have been cancelled. It is hoped that we will be able to visit Manston later in the Summer.

On the 17th March the Section visited the Fairey factory at Hayes. Particularly interesting was the Gannet production and assembly line and the system of envelope jigging used in the aircraft's construction. The use of high tensile steel castings produced by investment processes in the Company's own Foundry, was noteworthy and a number of major structure members are formed of these components.

An associated activity was the Hydrobooster power control production line. The surface finishes, produced by hand lapping, have to be seen to be believed.

On Saturday 7th April we visited the R.A.F. Station, West Malling, which operates day and night fighter versions of the Meteor. The tour covered various sections of the Station including Air Traffic Control and the station workshops, where the radar side was of especial note.

Our future programme includes visits to Handley Page at Cricklewood and Radlett in early June, where there should be a great deal to see, and to Boscombe Down in July or August. This latter visit will be on a week day in order to see the establishment at work and travel will be by means of coach. Intending visitors should apply to their firms for leave of absence which is often given for Section visits of this nature.

We also hope to visit a Boeing B-47 base sometime during the Summer.

LECTURES:

The last lecture of the session will be given by Sir Frederick Handley Page on Thursday 10th May on "Some thoughts on present-day aircraft and the Future." Sir Frederick's brilliance as a speaker is well known and his subject should be full of interest for those intending managing directors in our ranks.

SPECIAL EVENT!

The Section is giving an informal Summer Party at 4 Hamilton Place on Friday 22nd June. Make a note of this date now and come along and bring your friends. Tickets, which will include a number of good things, will cost around 5/-.—P.A.H.

THE LIBRARY

Reviews

WINGS. *Blanche Stillson. Victor Gollancz, London. 1956. 299 pp. Illustrated. 16s.*

This book is in many ways fascinating, but I cannot agree with J. P. Marquand's remark on the dust-cover that it has an appeal similar to that of Rachel Carson's "The Sea Around Us." It somehow lacks the feeling of authority that imbues "The Sea Around Us." I have asked myself whether the fact that I know more about aerodynamics than about the sea may have a bad influence. It is difficult to tell.

The book is in three parts: Insects, Birds and Men. The big problem of the insect is the "why?" of the beginning and then the "how?" It is clear that we know very little about these, but I feel that Miss Stillson rather muffs it. I think that Snodgrass in this JOURNAL (Vol. 37, Feb. 1933, p. 113) did a better and more convincing job on this aspect, without using too many words. The chapters on Differentiation, Forms and Functions, Tokens of Maturity, Wings in Action and Double Duties are all most instructive and easy to read. The other two chapters in this section, on sound-producing wings, are not really relevant to the subject.

I think the insect part is the best of this book. The chapter on the Feathered Wing which introduces the bird section is good and straightforward, as is the part chapter on Discontinued Models. I do not know why the bat should have been wedged in with discontinued models. It is by no means discontinued and can do things no bird could do. Admittedly Miss Stillson does not say the bat is out, but she deals with it in the wrong company. The chapter on Flightlessness is also interesting, but of course it does not involve wings to any extent. Miss Stillson is least acceptable when she gets into aerodynamics. When she writes: "It is said that an airplane produces maximum lift when an angle of about 16° is reached" and goes on to say that birds can do better and says that a vulture can fly at 28°, her words become nonsense. Why compare slotted with unslotted wings? What about aspect ratio? Why not compare a delta with the albatross?

The propulsive power of the outer part of a bird's wing is not due to the fact that "its feathers are streamlined." That word "streamlined" is a fetish to the non-technical. Miss Stillson is not talking to technical people, but is it right to make false statements using everyday words because the right words may not be too easily understood? Surely with skill and practice any technical concept can be explained correctly in everyday language. But some other statements are just plain wrong, such as: "Deprived of the 'negative pressure' above that is engendered by speed, the slow-flying bird must obtain lift by increasing the 'positive' pressure from below." If it were not for the fact that the following appears in both the U.K. and U.S.A. editions, I would have ignored it as a misprint: "By one means or another every bird at the commencement of flight must attain a velocity greater than that of the air through which it moves."

One of the most interesting aspects of bird flight is the interplay of wing loading, aspect ratio and all-up weight. Miss Stillson thinks it is a curious fact that wing area does not increase in direct proportion to the weight of the bird. It may be curious, but it is certainly to be expected. Lachmann in 1932 in this JOURNAL (Vol. 36, April 1932, p. 374) explained this interplay very clearly using facts supplied from a paper by R. R. Graham, also in this JOURNAL, in 1932 (Vol. 36, Jan. 1932, p. 24). Miss Stillson does not clearly state the problem or its answer. The facts that the smaller birds need a lower power loading than large birds because they need to manoeuvre more, and that in the larger birds the structure weight increase has to be paid for by a higher power loading so that manoeuvre is limited, are not brought out.

Getting away from aerodynamics and structures, Miss Stillson does very well in her descriptive-observational sections, such as that on flapping flight and some of her remarks on gliding and soaring of birds.

Miss Stillson's 87 pages on Men are not as good as her sections on Insects and Birds. Not only that, but they end where the real interest begins, on 17th December 1903.—B. S. SHENSTONE.

MEDICAL HISTORY OF THE SECOND WORLD WAR—ROYAL AIR FORCE MEDICAL SERVICES, VOL. 2: COMMANDS. *Edited by Squadron Leader S. C. Rexford-Welch. Her Majesty's Stationery Office, London, 1955. 703 pp. Illustrated. 75s.*

This second volume of the Royal Air Force Medical Services' contribution to the Medical History of the Second World War deals with the part they played in the activities of the various Commands—Bomber, Fighter, Coastal, Transport, Balloon, Army Co-operation, Maintenance, Flying Training, Technical Training, Second Tactical Air Force, also 60 Group (Radar) and the Royal Air Force Regiment.

Although much of this history is mainly of value to those in the Services, there are many items of general interest to all those engaged in aviation. For example, the various problems of aviation medicine covering such subjects as the development of efficient oxygen installations, both fixed and portable; the effects of decompression and how to guard against these; cockpit lighting systems to preserve dark adaptation and give good legibility of instrument readings and maps; the testing for night vision capacity, and, even more important, training to see in the dark; methods of heating and ventilating cockpits and cabins; in-flight and emergency rations; the best crash positions to adopt and escape drills; also flying stress and fatigue and how to prevent these. The results of observations, researches and experience in these matters during the war paved the way for commercial aviation to select the best types of installations for comfort, efficiency and safety in flying in present day aircraft.

In addition, the sections on parachute training, and on the air sea rescue and the mountain rescue services, are full of interest and sound practical advice. The chapter on Ferry and Transport Commands, who had the co-operation of the B.O.A.C., gives a good insight into the problems in those pioneer days of anoxia, cold, in-flight feeding, sanitation and health in long distance flights across the Atlantic and Africa. Comparison with conditions in air liners plying these routes today shows the great progress that has been made; this would have been much slower without the vast experience garnered by this wartime endeavour. This chapter should be read, if only to pay homage and thanks to those pioneers, both Service and Civil.—H. E. WHITTINGHAM.

STRENGTH AND ELASTICITY OF MATERIALS AND THEORY OF STRUCTURES. SOLUTIONS TO EXAMINATION QUESTIONS. *W. H. Brooks. Macdonald, London, 1953-1956. Vol. I, 223 pp., 15s. Vol. II, 196 pp., 18s. Vol. III, 317 pp., 25s. Vol. IV, 464 pp., 35s.*

All four volumes contain solutions to questions set in the London University Degree examination from approximately 1937 to 1953. Volumes I and II deal with PART I B.Sc.(Eng.) internal and external examinations respectively in Strength and Elasticity of Materials and Theory of Structures and cover simple stress and strain, bending and torsion, deflections, resilience, simple struts, plane frames, arches, rolling loads and simple influence lines. Volumes III and IV deal with PART II B.Sc.(Eng.) internal and external examinations in Strength and Elasticity of Materials and cover encastré beams, compound stresses, curved bars, temperature stresses, struts, elastic constants, shear deflection, springs, thick and thin tubes, strain energy and vibration.

These volumes are of considerable value to students and lecturers, particularly external students, some of whom may be pursuing part-time study only. The solutions are given in considerable arithmetical detail and include descriptive matter and various theoretical proofs. Adequate theoretical knowledge is assumed.

The author has obviously given considerable attention to his manner of presentation and provides both subject and examination paper indexes. Answers only are given to some examples and consideration is given to the revised London Degree regulations. Insufficient attention is paid to sign convention, however, and a note on this, rather than a reference, would be helpful. An inevitable criticism, particularly for the more advanced examples in Volumes III and IV, is that methods of solution can differ widely with various lecturers and there could therefore be a tendency to confuse the student.

In all, a most useful work for all intending engineers. However, it undoubtedly focuses on the all-important examination period and leaves one with the feeling that present methods of assessment by examination have now outlived their usefulness and should be replaced by methods which take into account all work effected during the full period of student learning.—K. L. C. LEGG.

BEARING LUBRICATION ANALYSIS. *R. R. Slaymaker. John Wiley, New York, 1955. 108 pp. Illustrated. 40s.*

This is a concise book in which the aim of the author is to lay down a good foundation for bearing design. It is written primarily for engineering college students and practising engineers not too familiar with the subject.

Dealing entirely with the journal bearing, the reader is led easily to the solution of the Harrison-Sommerfeld equation, the important features of which are pointed out on the way. Some of the mathematical steps are left out but the treatment is full enough to allow a proper insight to be gained into the underlying principles of pressure formation in the oil film. The mathematics are lucidly illustrated with line diagrams and these, with the physical explanations of some of the equations, make an easy grasp of the subject possible.

Since the book is not written for the lubrication specialist, the full theoretical treatment is abbreviated. For example, the theory of end-flow in bearings is not given. However, the effects are described and tables included in the text which allow the designer to take them into account. At all times the application of the results to bearing design is kept well to the forefront by many practical examples and case studies.

The subject of oil viscosity is adequately dealt with and its importance in bearing lubrication is stressed. Various types of sleeve bearing are considered and their construction described. The properties of bearing materials in the light of pertinent performance aspects are also discussed.

Throughout the book the important part played by temperature and its effects on the properties of both lubricant and bearing material is kept in mind. The interplay of oil viscosity and bearing clearance, etc., as affected by temperature is fully discussed. Helpful guidance on methods of predicting the temperature rise of bearings is given. A short account of boundary lubrication and oil-less bearings concludes the book.

The book achieves its object of pointing out the essential features of bearing lubrication and relating them to bearing design in a very practical manner. For those who wish to study particular aspects further references to other works are given in each chapter.—T. B. LANE (Thornton Research Centre).

Additions to the Library

Aluminium Development Association. PROPERTIES OF ALUMINIUM AND ITS ALLOYS. 1956.

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Taylor, J. W. R. CIVIL AIRCRAFT MARKINGS. Ian Allan. 1956.

Warren, A. LET'S LEARN TO FLY. Pitman. 1956.

**Items marked thus are for reference use only.*

Reports

AERODYNAMICS

Boundary Layer

See also Thermo-Aerodynamics

The three-dimensional boundary layer flow about a yawed ellipsoid at zero incidence. J. A. Zaat et al. N.L.L. Report F. 165 (*January* 1955).

Using Timman's two parameter method for three-dimensional laminar boundary layers, the velocity distribution in the laminar boundary layer of a yawed ellipsoid at zero incidence are calculated. The momentum equations in stream line direction and perpendicular to this direction can be reduced to a set of quasi-linear first order partial differential equations. The initial conditions are determined from the behaviour of the differential equations in the stagnation point.—(1.1.1).

Compressible Flow

The zero-lift drag of full and half models of a body of revolution at $M = 1{\cdot}6$. *J. A. van der Bliek. N.A.E. Canada. Note* 11 (*LR*-139). (1955).

The zero lift drag of full and half models of a body of revolution was measured in the N.A.E. 10- × 10-inch and the 30- × 16-inch wind tunnels at $M = 1{\cdot}6$ and $R = 2{\cdot}8$ to 6 million. Different methods of boundary layer flow visualisation and artificial transition were utilised. With a half model the effect of tunnel wall boundary layer shim thickness was investigated.—(1.2.3).

An integral equation theory for the transonic flow around slender bodies of revolution at zero incidence. F. Keune and K. Oswatitsch. K.T.H. Aero T.N. 37 (1954).

The integral equation for calculating the flow over slender bodies of revolution which are pointed at the front and rear is derived by the method of K. Oswatitsch using the gas dynamic equation for axisymmetric transonic flow. A certain function is assumed for the variation in velocity at radial distances from the body. The integral equation can thus be reduced to line integrals for calculating the velocity on the axis of the body. The integrals are analysed into finite sums of strips of equal width. The coefficients of this numerical integration are calculated separately as matrices.—(1.2.2.1).

A second-order shock-expansion method applicable to bodies of revolution near zero lift. C. A. Syvertson and D. H. Dennis. N.A.C.A. T.N. 3527 (*January* 1956).

A second order shock expansion method applicable to bodies of revolution is developed by the use of the predictions of the generalised shock expansion method in combination with characteristics theory. Equations defining the zero lift pressure distributions and the normal force and pitching moment derivatives are derived. Comparisons with experimental results show that the method is applicable at values of the similarity parameter, the ratio of free stream Mach number to nose fineness ratio, from about 0·4 to 2.—(1.2.3).

Design criteria for axisymmetric and two-dimensional supersonic inlets and exits. J. F. Connors and R. C. Meyer. N.A.C.A. T.N. 3589 (*January* 1956).

Design charts for single and double oblique shock inlets and for a systematic family of isentropic axisymmetric and two-dimensional surfaces, suitable for either inlet or exit applications, are presented for Mach numbers up to 4·0. For isentropic inlets having a mass flow ratio of unity and focused compression at the cowl-lip, compression limits based either on shock structure or cowl shock attachment requirements are analysed and evaluated. At a Mach number of 4·0, an all external compression isentropic inlet is limited to a theoretical total pressure recovery of 0·685 based solely on shock losses.—(1.2.3. × 1.5.1.).

Internal Flow

See also Compressible Flow

An experimental investigation of a thick-aerofoil nozzle cascade. S. J. Andrews and N. W. Schofield. R. & M. 2883 (1956).

The cascade tests on a thick aerofoil turbine nozzle blade suitable for a cooled turbine show that it has a good performance over a wide incidence range up to $M = 0{\cdot}8$. Above this value the loss coefficient rises and does not fall again as $M = 1{\cdot}0$ is approached. Several methods of indication of the transition point have been tried and results show that the method depending on the evaporation of crystals gives a position inconsistent with three other methods, *i.e.*, lamp-black deposit, surface total head measurement and stethoscope search tube.—(1.5.4.3).

Model tests on the asymmetry of airflow occurring in twin-intake systems at subsonic speeds. J. Seddon and W. J. G. Trebble. R. & M. 2910 (1955).

In twin air-intake systems (*i.e.*, a pair of intakes discharging into a common duct or chamber) in which the losses are affected by external boundary layers, asymmetry of flow between the two ducts occurs below a certain critical value of the flow coefficient (entry velocity/free stream velocity). The effects of this asymmetry on intake efficiency, and more particularly on flow distribution at the compressor, may be important. If, as seems possible, the flow oscillates between the two sides, this may give rise to vibration of the aircraft. Wind tunnel model tests have been made on a pair of wing-root leading-edge intakes and on various arrangements of body-side submerged intakes. In all cases a region of flow asymmetry was observed. The appropriate flow coefficients are outside the main working range of the intakes, but are such as might be encountered in a dive, or on suddenly throttling back in level flight.—(1.5.1).

Measurement of the derivative z_w *for oscillating wings in cascade. R. D. Milne and F. G. Willox. C. of A. Report No.* 93 (*July* 1955).

Experimental results are reported of the damping derivative z_w for rigid rectangular wings of various aspect ratios in cascades having gap-chord ratios of 2, 1, ½, 1/3, ¼. The results show fair agreement with two-dimensional theory. The ranges of Reynolds numbers and frequency parameters were 0·8 to $2{\cdot}5 \times 10^5$ and 0·1 to 0·45 respectively.—(1.5.4).

Luftströmungen mit Drall im Kreisrohr hinter radialem Leitapparat. W. Schiebeler. Max-Planck-Institut. Nr. 12 (1955).—(1.5.1.).

Stability and Control

The unsteady aerodynamic forces on deforming, low aspect ratio wings and slender wing-body combinations. R. D. Milne. C. of A. Report No. 94.

A method is presented whereby the "Slender Body Theory" can be applied to the determination of the unsteady aerodynamic forces acting on slender wings and wing-body combinations experiencing harmonic deformations in a compressible flow. The analysis holds for subsonic and supersonic speeds, subject to restrictions which are stated and discussed. A simplification of the method is also introduced which is applicable to many practical cases and calculations are performed on this basis which lead to numerical results for "Equivalent Constant Derivatives" for a deforming slender delta wing using modal functions which are polynomials of the spanwise parameters; and "Rigid" Force Coefficients for a pitching and plunging, slender, wing-body combination.—(1.8.0.2).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

A method for the determination of the damping-in-pitch of semi-span models in high-speed wind-tunnels, and some results for a triangular wing. K. Orlik-Rückemann and C. O. Olsson. F.F.A. Report 62 (1956).

A method has been developed for the determination of the damping-in-pitch of semi-span models in high-speed wind tunnels using free oscillation technique. The model is mounted elastically by means of a torsion bar with cruciform section. The initial oscillation amplitude is built up electromagnetically, after which the disconnection of the energy source results in a free oscillation, which is automatically evaluated on a special electronic apparatus, called the "Dampometer." The method is used to determine the damping-in-pitch of a semi-span model of a triangular wing of aspect ratio 1·45 oscillating around the 60 per cent. point at subsonic, transonic and supersonic speeds.—(1.8.2.2).

Directional stability of towed airplanes. W. Söhne. N.A.C.A. T.M. 1401 (*January* 1956).

A theoretical investigation of the lateral dynamic stability of an aeroplane towed by a single towline is presented, and the equations of motion are derived. The effects of variations of towline length, attachment point, lift coefficient, model mass, and angle of climb are examined. In addition, the effects of changes in dihedral, tail area, and damping in roll are studied.—(1.8.1).

A preliminary investigation of the effects of frequency and amplitude on the rolling derivatives of an unswept-wing model oscillating in roll. L. R. Fisher et al. N.A.C.A. T.N. 3554 (*January* 1956).

The low-speed yawing moment due to rolling and the damping-in-roll derivatives were obtained from forced oscillation-in-roll tests. These data are presented chiefly for an angle of attack of 0° for a complete model and its various components through a range of frequencies and amplitudes of the rolling oscillation. Comparisons between the oscillation results and steady state results from conventional rolling flow tests are made.—(1.8.1.2).

THERMO-AERODYNAMICS

Experimental investigation of air-flow uniformity and pressure level on wire cloth for transpiration-cooling applications. P. L. Donoughe and R. A. McKinnon. N.A.C.A. T. N. 3652 (*January* 1956).

An experimental investigation was conducted to obtain information on air flow uniformity and pressure level effects for various meshes of stainless steel corduroy wire cloth, and permeability and strength data for a 20×200 mesh stainless steel wire cloth.—(1.9.1 × 1.1.5).

WINGS AND AEROFOILS

Choking effects and some Reynolds number effects on the Mach number distribution round a two-dimensional aerofoil in the R.A.E. 10-ft. × 7-ft. high-speed tunnel. D. A. Clarke and H. E. Gamble. R. & M. 2912 (1955).

A two-dimensional aerofoil of N.A.C.A. 0015 section was tested at zero incidence in the Royal Aircraft Establishment 10 ft. × 7 ft. High-speed Wind Tunnel and measurements were made of (*a*) Static pressure on the aerofoil surface at Reynolds numbers of $1{\cdot}4 \times 10^6$ to $5{\cdot}5 \times 10^6$. (*b*) Static pressure on the aerofoil surface, on the tunnel walls and in the stream between the aerofoil and the walls at $R = 2{\cdot}8 \times 10^6$. All the tests were made at Mach numbers of 0·7 upwards and were continued past the choking Mach number of 0·764 until either the maximum permissible fan speed was reached or the maximum available power was being used.—(1.10.2.1).

*The flow around a supersonic aerofoil. J. J. Mahony and P. R. Skeat. A.R.L./A.*147 (*October* 1955).

An approximate solution is presented for the rotational, completely supersonic flow of a perfect, inviscid gas about a sharp-nosed two-dimensional aerofoil. It is based on the neglect of terms which are of second order in the entropy changes across the shock waves so that, for reasonable values of this thickness ratio, the errors thus introduced will be unimportant.—(1.10.11).

Remark on the theory of lifting surfaces. A. Muggia. N.A.C.A. T.M. 1386 (*January* 1956).

First, the Weissinger method, as it applies to a rectangular wing, is discussed. By building on this framework it is shown how to treat the lift problem for any thin wing of arbitrary plan form.—(1.10.1.2).

HELICOPTER AERODYNAMICS

Helicopter rotor behaviour after engine failure in forward flight. W. Stewart and M. F. Burle. R. & M. No. 2861 (1955).

Caluculations have been made to find the changes in rotor speed following engine failure in forward flight. Several particular examples were investigated, based on the parameters of the S-51 helicopter. The effect of pilot's control movement was included.—(1.11.2).

TESTING AND INSTRUMENTS

Quelques balances à jauges extensométriques des souffleries françaises. P. Rebuffet. O.N.E.R.A. N.T. 31 (1956)—(1.12.4).

Mesure et enregistrement des mesures sur les balances aérodynamiques à jauges à fil résistant. M. Bassière. O.N.E.R.A. N.T. 32 (1956).—(1.12.6).

Fabrication de maquettes à l'aide des matières plastiques. G. Dixmier. O.N.E.R.A. N.T. 33 (1956).—(1.12.1).

Instrumentation for measurement of free-space sound pressures in the immediate vicinity of a propeller in flight. W. D. Mace et al. N.A.C.A. T.N. 3534 (*January* 1956).

Instrumentation suitable for the measuring, recording, and subsequent harmonic analysis of the free space sound pressures in the immediate vicinity of an aeroplane propeller at flight Mach numbers up to 0·72 is described. The dynamic range of the equipment is 150 to 113 decibels (re 0·0002 dyne/cm²) and the system frequency response is flat within ±1 decibel from 80 to 1,000 c.p.s.—(1.12.6.6).

Investigation of the effect of short fixed diffusers on starting blowdown jets in the Mach number range from 2·7 *to* 4·5 *J. A. Moore. N.A.C.A. T.N.* 3545 (*January* 1956).

An investigation was made at Mach numbers of 2·7, 3·0, 3·5, 4·0, and 4·5 to determine the effect of short fixed convergent-divergent wedge diffusers on the starting characteristics of blow down jets exhausting to the atmosphere. Wedge diffusers that were extensions of the nozzle contours reduced the overall pressure ratios required for starting to less than one-half the values obtained without a diffuser.—(1.12.1.3).

AEROELASTICITY

Flutter problems of high-speed aircraft. E. G. Broadbent. R. & M. 2828 (1955).

The flutter problems of high-speed aircraft are considered generally and specific consideration is then given to the new problems introduced by the use of new wing plan forms. The theoretical and experimental results on the coupled ("classical") symmetrical flutter of swept (including "barbed" and cranked forms) and delta wings are reviewed and presented to show the effect and importance of the body freedoms of the aircraft on the critical flutter speed and frequency.—(2.0).

The geared elevator tab and tail-unit stiffness requirements. Ll. T. Niblett. R. & M. 2848 (1955).

The effect of a flexible, geared, elevator tab upon the validity of the stiffness criteria for tail-units and rear fuselages is examined. To this end, the distortions of a hypothetical, semi-rigid tail-unit under the air loads induced when the elevator is displaced are calculated for various arrangements of tab and forward aerodynamic balance of the elevator. Notice is also taken of the loss of control effectiveness and change in elevator hinge moment resulting from these distortions.—(2.0).

Spring tab flutter. Part 1. *A theoretical investigation on wing-aileron-tab flutter. R. A. Frazer and W. P. Jones. Part II. Experiments on binary aileron-tab flutter. C. Scruton, J. Williams and C. J. W. Miles, et al. R. & M. No.* 2952 (1955).

Part I discusses theoretically wing aileron tab flutter, with special reference to the influence of spring tab control. Numerical applications of the theory are made to two representative types of spring tab, and with the aid of special diagrams certain conclusions are drawn regarding the conditions for flutter prevention. Part II describes experiments which were made to test certain of the conclusions of Part 1 for binary aileron tab flutter.—(2.0).

DESIGN AND CONSTRUCTION

Investigation of the propulsive characteristics of a helicopter-type pulse-jet engine over a range of Mach numbers and angle of yaw. P. J. Carpenter et al. N.A.C.A. T.N. 3625 (*January* 1956).

The non-whirling propulsive characteristics of a helicopter-type pulse-jet engine mounted on a simulated rotor blade have been determined in the Langley 16-foot transonic tunnel. A propulsive thrust of about 1 lb/sq. in of engine frontal area at Mach numbers from 0·25 to 0·45 was obtained. Propulsive thrust at Mach number 0·6 decreased to about 0·73 lb./sq. in frontal area.—(4.4 × 27.4).

AIRCRAFT OPERATION

Effect of climb technique on jet-transport noise. W. J. North. N.A.C.A. T.N. 3582 (*January* 1956).

A theoretical investigation of jet-transport climb technique was made to determine the effect of variations in engine thrust and air speed on sound pressure levels heard by a ground observer. Reduced noise levels will be obtained when climbing on the steepest flight path consistent with minimum safe air speed.—(5.5).

Investigation of far noise field of jets: I—Effect of nozzle shape. E. E. Callaghan and W. D. Coles. N.A.C.A. T.N. 3590 (*January* 1956).

The noise generation of jets discharging from convergent (circular, square, rectangular, and elliptical), plug, and convergent-divergent nozzles was investigated. At low jet pressure ratios (less than 2·2) all the nozzles had approximately the same sound field. At high pressure ratios, all the nozzles produced noise having discrete frequency peaks. Only the convergent-divergent nozzle showed a reduction in both amplitude of the discrete frequency noise and in total sound power radiated as compared with ordinary convergent nozzles.—(5.5 × 27.1).

Investigation of far noise field of jets: II—Comparison of air jets and jet engines. W. D. Coles and E. E. Callaghan. N.A.C.A. T.N. 3591 (*January* 1956).

A comparison of the noise generation of air jets and turbot jet engines was made from data obtained from similar free field surveys. At jet pressure ratios below or only slightly above that for choked flow, the overall sound power was well represented by the Lighthill parameter, but the sound power results obtained during afterburner operation were somewhat low. Directional patterns for overall sound pressures were similar for the engines and air jets. Air-jet and engine spectral data were dissimilar because of a dip in the engine noise spectrum.—(5.5 × 27.1).

FUELS AND LUBRICANTS

Comparaison de la résistance au choc des films lubrifiants. F. Charron. Publications Scientifiques et Techniques. No. 298 (1955).—(14.0).

Fluides de transmission en aéronautique. F. Meiller et F. Reynaud. O.N.E.R.A. note technique No. 28 (1955).—(14.0).

Experimental and calculated temperature and mass histories of vaporizing fuel drops. M. M. El Wakil, R. J. Priem, et. al. N.A.C.A. T.N. 3490 (*January* 1956).

Experimental and calculated mass and temperature histories of drops vaporising with a constant velocity relative to the air velocity are compared herein, and it is confirmed that, under many conditions, the unsteady state or time required for the drop to reach the wet-bulb temperature is an appreciable portion of the total vaporisation time.—(14.0).

Spontaneous ignition studies relating to lubricants of reduced flammability. K. T. Mecklenborg. N.A.C.A. T.N. 3560 (*January* 1956).

Increased interest in the use of diesters as lubricants has suggested a study of the influence of the structure of the alcohol moiety on the spontaneous ignition temperature of a series of dialkyl azelates. The determination of spontaneous ignition temperatures has been extended to a number of representative organic phosphorous esters with predominantly aliphatic structures.—(14.3).

HYDRODYNAMICS

A full-scale investigation into the hydrodynamic behaviour of a highly faired flying-boat hull. J. A. Hamilton. R. & M. 2899 (1956).

The hydrodynamic qualities of a Sunderland flying-boat hull, weight 50,000 lb., fitted with a main-step fairing of fairing ratio 17:1 are investigated. The fairing was equipped with ventilating ducts, drawing air at atmospheric pressure through ports on the hull side, and discharging it through exit vents on the afterbody planing bottom. No pumping apparatus was fitted, the air flow being induced by the sub-atmospheric pressures on the fairing.—(17.2).

Hydrodynamic impact loads in smooth water for a prismatic float having an angle of dead rise of 10°. *Philip M. Edge, Jr. N.A.C.A. T.N.* 3608 (*January* 1956).

Hydrodynamic-load data obtained at the Langley impact basin from tests of a prismatic float with an angle of dead rise of 10° are presented. Tests were made at fixed trims of 3°, 12°, 20°, and 30° and a range of flight-path angles from 2° to 23°. The data are presented as dimensionless coefficients and experimental values of dead-rise function and aspect-ratio factor are obtained.—(17.2).

INSTRUMENTS AND EQUIPMENT

An oil-stream photomicrographic aeroscope for obtaining cloud liquid-water content and droplet size distributions in flight. P. T. Hacker. N.A.C.A. T.N. 3592 (*January* 1956).

An airborne cloud aeroscope by which droplet size, size distribution, and liquid-water content of icing and non-icing clouds can be determined has been developed and tested in flight and in wind tunnels with water sprays. The cloud droplets are continuously captured in a stream of oil, which is then photographed. In most cases, droplet size distribution can be obtained from a single photograph. With the droplet size distribution known, the liquid-water content of the cloud can be calculated from the geometry of the aeroscope, the air speed, and the oil flow rate.—(18.4).

MATERIALS

Variations in the strength of aluminium alloy sheet. D. T. Jones. C.P. 229 (1956).

In the design of aircraft structures allowance is made for variation in the material strength of sheet but the thickness of the sheet is usually assumed to be constant at the nominal value for the gauge used. Thickness variation may appreciably affect the tensile strength of nominally identical pieces of sheet, especially when the tolerance range in thickness is wide. A method is given for calculating the distribution of strength when the mean and scatter of material strength and the mean and scatter of thickness of pieces are known. Expressions are given for the mean and scatter in strength of pieces, for those cases where the distribution of the strength can be taken as normal, design values can readily be deduced from the expressions.—(21.2.2).

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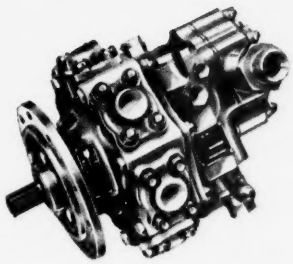

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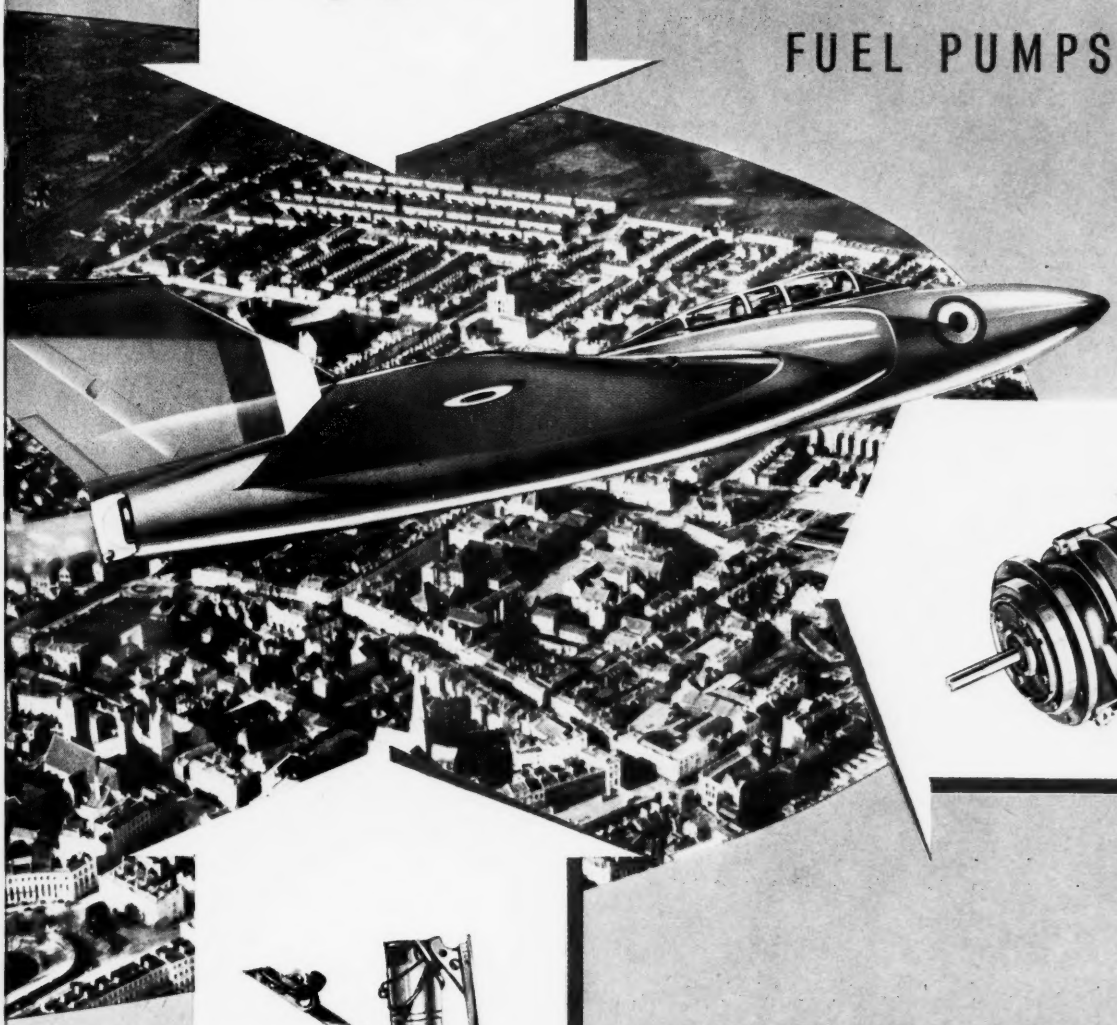

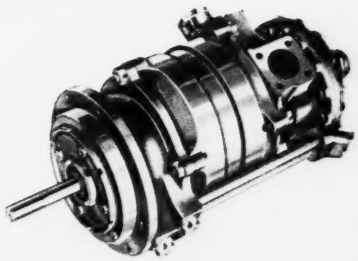

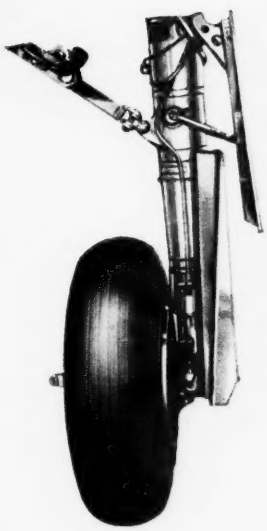

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